Investigation of process conditions for catalytic conversion of carbohydrates by epimerization using a microstructured reactor

Berta Spasova[a,*], Christof Kuesters[b], Bruno Stengel[b], Juergen J. Brandner[a]

[a] Karlsruhe Institute of Technology, Institute for Micro Process Engineering, Campus North, Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany
[b] Cargill R&D Centre Europe, Havenstraat 84, B-1800 Vilvoorde, Belgium

A B S T R A C T

The epimerization of carbohydrates with molybdate catalysts has been investigated using a microstructured reactor. Parametric screening tests were performed with different catalyst concentrations ranging from 0.02 wt.% to 0.2 wt.%, with and without H_2SO_4, in the temperature range from 130 °C to 200 °C and at different total flow rates from 1 ml/min to 10 ml/min.

The results achieved by this current work show that the addition of H_2SO_4 for the reaction is not necessary. The molybdate-catalyzed conversion in a microreactor in continuous flow regime provides especially high yield of mannose to approx. 30–32% at $T_{Reaction} = 160$–200 °C with catalyst concentration of 0.2 wt.%. The tested reaction in a microstructured reactor needs a smaller flow rate in the area between 1 ml/min and 2 ml/min, which results in a longer residence time. No by-product like hydroxymethylfurfural (HMF) was observed with the tested catalyst concentration of 0.1 wt.%. The ratio of glucose to mannose changes from 3:1 to the range (1.7-2):1.

The continuous flow operation in a microstructured reactor exceeds the previously known yield of mannose with a ratio 3:1 found in actual literature data.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

The first example of an epimerization in general, the C2-epimerization of aldoses using the molybdate-catalyzed reaction from D-glucose to D-mannose, was observed in 1972 by Bilik [1]. This study presents the optimal conditions of hydroxylation of D-galactal by the preparation of D-talose in the presence of molybdate ions in water solution. The tested catalysts of Na_2MoO_4, MoO_3, Na_2WO_4 and WO_3 for the hydroxylation showed that the stereo-selectivity of the reaction was enhanced by the replacement of MoO_3 with Na_2MoO_4 and smaller amount of both epimeric aldose-galactose and 2-deoxy-D-lyxo-hexose was formed as by-products as a consequence of the reduced acidity of the reaction medium [1]. The same type of reaction catalysed by molybdate ions was applied for the transfer of L-mannose to L-glucose in water solution under the catalytic action of molybdic acid, which gives an equilibrium mixture of the epimeric aldoses L-glucose and L-mannose in the ratio 75:25 [2] and α-methyl D-mannopyranoside from D-glucose [3]. The mechanism of the Bilik reaction does not involve the above mentioned ene-diol transition

state in contrast to the Lorby de Bruyn-Alberda van Ekenstein epimerization from glucose or fructose, which proceeds through an ene-diol transition state [4,5]. The C2-epimerization is presented schematically in Fig. 1.

The applying of molybdate catalysts has gained importance for those processes, where the Mo-ions are the active species and binuclear molybdate species forms a complex with the hydroxyl group at C1, C2, C3 and C4 carbon atom of the aldose in a first step. In this complex, the C2—C3 bond is simultaneously cleaved, whereas a new C1—C3 bond is formed (see Fig. 2). The process is accompanied by a dehydration/hydration step at the carbon atoms C1 and C2 [6].

The reaction of the epimerization is an intramolecular rearrangement leading to an equilibrium mixture of D-glucose and D-mannose in the ratio 73:27 [7]. During epimerization of D-glucose or D-mannose in water solution of molybdic acid the ratio between the epimers (D-glucose and D-mannose) is kept identical with equilibrium (i.e. 75:25). When the reaction is carried out at 90 °C the equilibrium is reached within 3 h with D-mannose and within 6 h with D-glucose. The epimerization of both saccharides catalysed by molybdate ions is schematically shown in Fig. 3 [8]. Similarly to this is the preparation of L-glucose by epimerization of L-mannose in aqueous media or L-mannose from its phenylhydrazone with
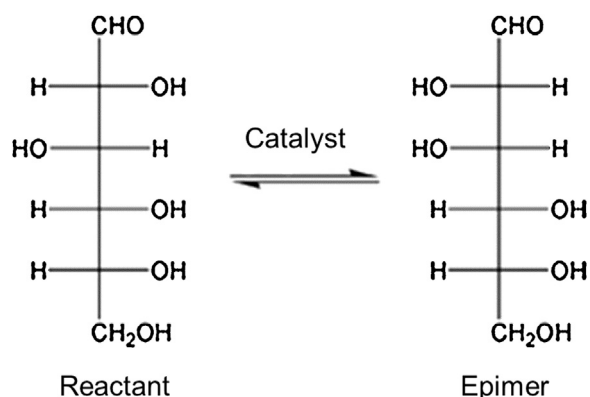
Fig. 1. Schematic representation of the epimerization.
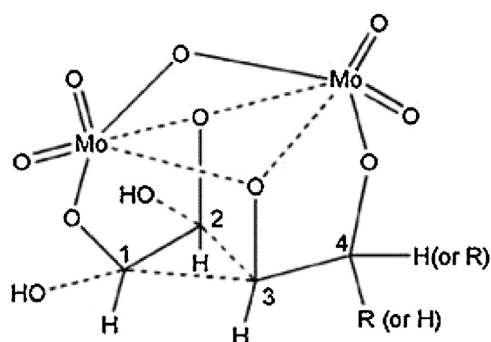

Fig. 2. Glucose-dimolybdate transition state formed by the Bilik reaction [6].

benzaldehyde in the presence of molybdic acid in a mixture of water and ethanol [2].

Tanase et al. [9] reported the C2-epimerization of aldoses based on the $[Ni(H_2O_2)_2(tmen)_2]Cl_2$ (tmen = N,N,N'-trimethyl-ethylene-diamine) catalyst. The nickel(II) ions form complexes with only the mannose-type epimers (D-mannose, D-lyxose, and D- or L-rhamnose) in a stereoselective way. The presented reaction is very fast in mild basic conditions (60 °C, 4 min) and involves the stereoselective uptake of mannose-type C2 epimers in a ratio of glucose:mannose = 45:55 from aldose (glucose) as reagent; a ratio of 34:66 comes from D-Mannose.
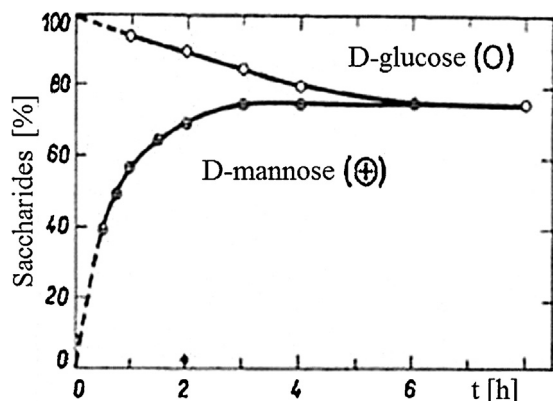

Fig. 3. Reaction of epimerization of D-glucose and D-mannose saccharides as a function of time [8].

Kolaric [10] studied the epimerization of D-glucose and D-mannose catalysed by water soluble organometallic complexes of Cu(II), Ni(II), Co(II) and Cd(II) with nitrogen ligands as well as by Mo(VI) complexes prepared in-situ from ammonium heptamolybdate with ligands 4–9. All the tested complexes exhibit lower catalytic activity than the ammonium heptamolybdate. Some free ligands and their metal (II) complexes catalyse both C2-epimerization and isomerization of aldoses to D-fructose. In all experiments the equilibrium mixture was reached after 90 min with a maximum ratio (water at 100 °C) of D-glucose:D-mannose:D-fructose = 44.2:12.0:43.8 (with [Ni(II)-4]). In methanol at 60 °C, the results show relative higher amounts of fructose with a ratio D-glucose:D-mannose:D-fructose = 30.8:12.7:56.6. For the C2-epimerization of D-glucose catalysed by [Mo-8] complex obtained in water at 100 °C, the study shows a ratio of D-glucose:D-mannose = 70:30 [10]

Sn-Beta zeolites with borate salts catalyze the epimerization of carbohydrates via an intermolecular carbon shift; this was reported by Gunther et al. [11]. The catalytic system consists of Sn-Beta and sodium tetraborate (SB) with the molecular formula $Na_2[B_4O_5(OH)_4]\cdot 8H_2O$ and the catalyst epimerizes aldoses to an equilibrium mixture containing the reactant (for example, glucose, xylose or arabinose) and the epimer (for example, fructose, xylulose and ribulose), without producing significant quantities of the ketose isomer (for example, fructose, xylulose and ribulose, respectively). With a 4:1 glucose:SB solution in the presence of Sn-Beta at a temperature of approx. 85 °C for 60 min, a product distribution of 84:1:15 glucose:fructose:mannose could be obtained [11].

Hricoviniova [12] investigated the effect of microwave irradiation on Mo(VI) catalysed transformations of reducing saccharides. Both pentoses and hexoses were converted to the corresponding epimers in considerably shorter reaction time. The yields achieved in this work were comparable to conventional methods. The compositions of the reaction mixtures obtained by Mo(VI)-catalyzed isomerization under conventional heating is glucose:mannose = 3:1, while with microwave irradiation it is glucose:mannose = 2.5:1.

In the present paper the catalytic conversion of carbohydrates by epimerization of glucose was studied as the reaction was performed in continuous flow in a microstructured reactor. Therefore it was tried to demonstrate the performance of carbohydrate epimerization in miniaturized equipment and to overcome the main disadvantages. On one hand there are the standards enzymatic or the biochemical processes, where the abundant sugars can be transformed into "rare" sugars by using three main classes of enzymes, namely keto-aldol isomerases, epimerases and oxidoreductases. On the other hand there are inorganic processes; the application of the inorganic solids (i.e. tin-containing silicates with Lewis acid character) can provide alternative chemical pathways to those of the biological systems. In contrast to enzymes, inorganic catalysts work over a larger range of reactant purities, temperatures, pressures and pH-values [11]. However, both process routes show main disadvantages, namely temperatures and long residence time. Moreover, in both the enzymatic and the inorganic epimerization process, a mixture of mannose and fructose is reached with relatively high content of fructose and particularly in most cases the complex nature of processes.

The study should show clearly the superior performance of the tested process and extremely high yield for mannose. It could be shown that in continuous mode of operation and using a microstructure reactor, the reaction results exceed the previously known yield of mannose in accordance with the literature data for the established reaction of Bilik et al. [1–3,7–8].