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Modified reactive SMB for production of high concentrated fructose syrup by isomerization of glucose to fructose

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Abstract

This work presents modifications to the Hashimoto's hybrid simulated moving bed reactor (SMBR) system which was used to produce 55% high fructose syrup (HFS55). The purpose of this study is to develop a new SMBR system to overcome the disadvantages of Hashimoto system (3-zone SMB with seven reactors), i.e., low utility of reactors when feed being a 50/50 blend of glucose and fructose. Two different configurations of modified system were presented in this paper: the first configuration is 4-zone SMB with one reactor, while the other one consists of one additional reactor. Both of these configurations aim at improving the concentration and purity of glucose at the inlet of the reactor, which will lead to both high productivity and high purity of fructose in the product. A state-of-the-art optimization technique, viz., non-dominated sorting genetic algorithm (NSGA) is used in finding the optimal design and operating parameters for the modified reactive SMB and Varicol processes. Compared with the Hashimoto's system, high productivity and purity of fructose can be achieved in these new systems using less number of reactors.

Keywords: Fructose; Moving bed bioreactor; Bioprocess design; Optimization; Varicol; Pareto

1. Introduction

The integration of chemical reaction and separation processes in a single unit can offer several advantages compared to a conventional process, e.g. less energy consumption, higher product yield and reduced capital investment. Examples for such multi-functional reactors are reactive distillation columns and chromatographic reactors. Unlike reactive distillation which combines chemical reaction and heat transfer, chromatographic reactor utilizes differences in adsorption affinities of the different components involved rather than differences in their volatility. It is especially suitable for the non-volatile or heat-sensitive reaction systems [1].

Among various types of chromatographic reactors, simulated moving bed reactor (SMBR) is so far the most successful implementation of a continuous countercurrent chromatographic reactor-separator [2]. SMBR system is designed to consist of a series of packed columns with feed entry and product withdrawal ports from the ends of different columns and with an appropriate sequence of column switching to simulate a countercurrent flow between the fluid and solid phase. If reaction occurs in the mobile phase, normally a soluble catalyst is fed into the reactor together with the desorbent. On the other hand, if reaction occurs in stationary phase, catalyst is usually immobilized on a carrier and mixed with the adsorbent [3]. An alternating arrangement of catalytically active and purely adsorptive chromatographic columns is also used for highly exothermic gas-phase reactions or reaction systems in which products are the strong retained species rather than the reactants [1,4].

SMBR can be applied both to gas-phase reactions (e.g., hydrogenation and partial oxidation reactions) and liquid-phase reactions (e.g., esterification reaction). Examples for gas-phase reactions are oxidative coupling of methane [4], as well as hydrogenation of mesitylene [5,6]. Applications for liquid-phase reactions include isomerization of glucose [7,8], inversion of sucrose [9], acetic acid esterification [10,11] and synthesis of MTBE by etherification [12].

Varicol [13], a modification of SMB system, also provides opportunity for coupling reactions. Unlike SMB, where the inlets and outlets shift synchronously at the end of the switching

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Nomenclature

a_v	specific surface area (m^2/m^3)
C	concentration in the molibe phase (mol/m^3)
d	diameter of columns
k	mass transfer coefficient (m/s)
K	distribution constant
K_e	equilibrium constant for reaction
K_m	Michaelis constant (mol/m^3)
L	length (m)
N	number of columns
PrF	net productivity of fructose (kg/s)
PurF	purity of fructose in the product
q	concentration in the solid phase (mol/m^3)
Q	volumetric flow rate (m^3/s)
Q_{R2}	volumetric flow rate to second reactor (m^3/s)
R	rate of the isomerization ($mol/m^3/s$)
T	temperature (K)
t	time (s)
t_{R2}	time period with flow to second reactor (s)
u	superficial liquid velocity (m/s)
V	volume (m^3)
X	conversion
z	axial distance (m)

Greek symbols

α	separation factor
χ	column configuration, $N_{S1}/N_{S2}/N_{S3}/N_{S4}$
ε	porosity

Superscripts and subscripts

0	initial
1,2,3,4	section 1, 2, 3, 4
a	adsorption
D	desorbent
e	equilibrium
f	feed
F	fructose
G	glucose
i	component i (G or F)
j	column j
m	maximum
N	Nth switching period
o	overall
P	product
R	reactor
Ra	Raffinate
s	switching
S	separator
T	total

period, the Varicol process is based on a non-synchronous shift of these ports. In Varicol, the global switching time is divided into several subinterval switching. The local switching of the ports is permitted in each sub-interval within a global switching period. Given the total number of the columns employed in a

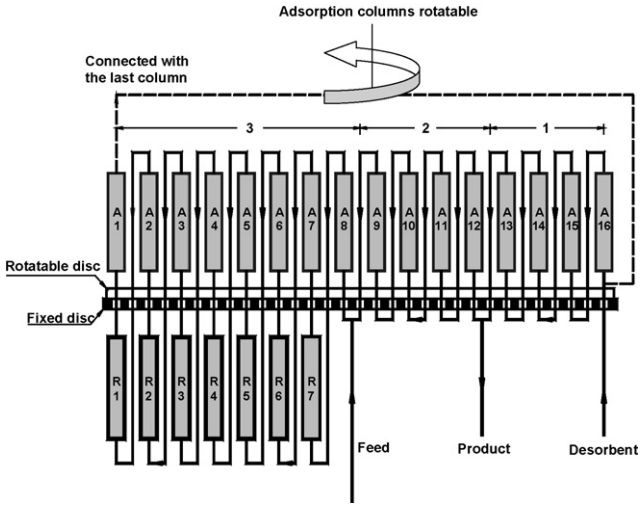

Fig. 1. Systematic diagram of Hashimoto's system with 7 reactors [7].

Varicol process, the number of the columns in each zone varies with time during a global switching period. As a result, Varicol can have several column configurations during the global switching period, which endows more flexibility compared to conventional SMB process. Varicol process shows significant improvement in terms of both product productivity and purity compared to traditional SMB. Such similar improvements have also been reported for reactive Varicol [14–17].

In the optimal design and operation of SMB bioreactor described in detail elsewhere [18], Hashimoto's hybrid SMBR system [7,8] (see Fig. 1) consisting of 16 adsorption columns and 7 enzymatic reactors, was optimized to obtain 55% concentrated high fructose syrup (HFS55) using experimentally verified dynamic SMBR model. This process was based on a partial integration of reaction and separation. Adsorption columns and reactors were alternatively arranged in zone 3 while zones 1 and 2 consisted of only adsorption columns. Characteristic for this process was that reactors were stationary while adsorption columns shift against the fixed inlet and outlet ports in the opposite direction of the fluid flow to simulate the countercurrent flow. The details of the system can be found elsewhere [7,18].

Although significant improvement of system performance had been achieved through multi-objective optimization study for the above system [18], it was observed that when feed is a 50/50 blend of glucose and fructose ($r_f = 1$), as shown in Fig. 2, the concentrations of fructose and glucose at the inlet of each reactor in zone 3 (Fig. 1) were about the same since equilibrium constant for the isomerization reaction is 1.0. As a result, conversion of glucose in each reactor was quite low. Previous studies [18] also suggested that modification based on the manipulation of the wave velocity does not yield much benefit for the system. Efforts should be made to increase the conversion of glucose within reactors. The purpose of the current study is to design modified SMBR system with fewer reactors, which can produce the equivalent amount of HFS55 by isomerization of glucose. This study also aims at finding the optimal design and operating parameters for the modified reactive SMB and Varicol system