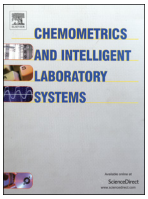
Chemometrics and Intelligent Laboratory Systems 158 (2016) 14–20

Contents lists available at ScienceDirect

Chemometrics and Intelligent Laboratory Systems

journal homepage: www.elsevier.com/locate/chemolab



Dynamic behaviors and nonlinear wave model control of heat integrated air separation columns with different purities

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ARTICLE INFO

Article history:
Received 1 October 2015
Received in revised form 8 August 2016
Accepted 13 August 2016
Available online 15 August 2016

Keywords:
Different purities
Heat integrated air separation column
Model predictive control
Nonlinear wave model
Shock wave velocity

ABSTRACT

Three heat integrated air separation columns (HIASCs) with different purities (low purity, moderate purity and high purity) are presented, and the open-loop dynamic behaviors are studied. A shock wave velocity is derived for HIASC, and based on that a nonlinear wave model of the HIASC is further established. Combined with the proposed wave model, a novel model predictive control scheme (SWMPC) is carried out, which is compared with a conventional model predictive control scheme (MPC). The comparison simulation results show that SWMPC can work better than MPC, especially for the high-purity HIASC.

1. Introduction

Many important industries like the iron and steel industry require quantities of industrial gases with different purities, and cryogenic air separation is a key part in the separation processes which is a common method used for producing industrial gases [1–3]. Since it consumes large amount of energy, any improvement of its energy efficiency could produce a significant impact on the economic profit in the industry [4–6]. The heat integrated air separation column (HIASC) has 40% more energy-saving potential than the conventional air separation column (CASC), which was studied and confirmed by many researchers [7–9].

However, high degree of thermal coupling brings complex influences on the dynamic behaviors in HIASC. Furthermore, there exist different characteristics among HIASCs with different product purities, such as the nonlinearity, sensitivity to external disturbances and asymmetry [10–14]. Thus many difficulties come out for modeling and controller design due to different structures of HIASCs with different purities [15–19]. Conventional models like the linear models cannot catch the nonlinearities of HIASC well and work with a low efficiency [20–25]. Conventional models based on data are not suitable either, because these models are employed for a certain structure and can only work in the neighborhood of certain operating point. However, when the structure and product purity change, the models become invalid [23,26–28]. So, an elegant control strategy based on an efficient model is required for HIASCs with different product purities.

With the development of distillation, a nonlinear wave theory, which proposes that systems with distributed parameters often exhibit dynamic phenomena which resemble traveling waves [29–32], is well used by Luyben for distillation columns, and he proposed profile position control of distillation columns with the propagation of temperature profiles [33]. Marquardt et al. and Hwang et al. [34–36] derived expressions for the wave propagation velocity and studied dynamic behaviors of concentration waves, respectively. The concept of coherence in nonlinear wave propagation was introduced by Helfferich et al. [37] to describe a state in which the concentration velocities of all components present within a composition are equal. Gruner et al. [38] developed a general framework for analyzing and understanding the dynamics of reactive separation processes based on equilibrium theory and nonlinear waves. A non-linear wave model for a distillation column had been extended by Hankins [39] and then examined by including enthalpy and hold-up effects, significant for wide boilers and leading to variable molar flows, and reflux and reboil. With the nonlinear wave theory introduced to the heat integrated distillation column (HIDiC), some researches were carried out for the internal thermal coupling technology. A completed nonlinear wave model of HIDiC was established by combining a novel wave velocity with thermal coupling relations and material balance relations by Liu et al. [40]. Then Liu et al. [41] developed a novel wave model based generic model controller (WGMC) of HIDiC processes. A simplified nonlinear wave model is established by Cong et al. [42], that concerns both the wave propagation and the profile shape, which is combined with an advanced controller to

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http://dx.doi.org/10.1016/j.chemolab.2016.08.008
0169-7439/

handle a very-high-purity system. However, there are few reports carried out about comparison analysis of dynamic behaviors for HIASCs with different product purities, and there are few general and efficient control designs suitable for HIASCs with different purities either.

In this work, three HIASCs with different purities (low purity, moderate purity and high purity) are studied, and the comparison analysis of open-loop dynamic behaviors is presented. A shock wave velocity is derived for both HPC and LPC of HIASC, and based on that a nonlinear wave model for HIASC is established which is much simpler and more effective than the traditional model. Combined with the proposed wave model, a novel model predictive control (SWMPC) is carried out, which is compared with a conventional model predictive control scheme (MPC) for HIASCs with different purities.

2. Systems studied

The HIASC is divided into two columns, which are high pressure column (HPC) and low pressure column (LPC). The gas nitrogen at the top of HPC and the liquid oxygen at the bottom of LPC are selected as the products of HIASC. Three HIASCs with different operation conditions and different product purities (low purity, moderate purity and high purity) are studied in the current work. The detailed operation conditions for each purity are shown in Table 1. The schematic diagram of HIASC and basic dynamic model equations consisting of material balance equations, equilibrium balance equations, summary equations, heat balance equations, etc. are provided in previous work [43].

3. Open-loop dynamic behaviors of different purities

The following dynamic behaviors are simulation results from the models mentioned in Section 2.

3.1. Nonlinearity

Fig. 1 shows the nitrogen product concentration responses to ± 10% step change from the initial value of manipulated variable HPC pressure in different purity conditions. N1 and N2 present the amplitude of positive and negative variations respectively caused by disturbances which are equal but opposite in direction. If the N2/N1 ratio is greater than 1, it means the negative responses are stronger than the positive responses which reveal nonlinearity of a system. So if the ratio becomes greater with the increasing purity, it reveals that when the purity of HIASC increases, the nonlinearity became stronger.

In the low-purity model, positive and negative disturbances lead to responses with a little bit difference, which shows that nonlinearity exists but it is not high. Thus linear model could describe the low-purity HIASC in some ways. The nonlinearity becomes obvious in the moderate-purity model, presented by N2/N1 = 1.7. Furthermore, N2/N1 increases to 5.4 in high-purity model. The intensified nonlinearity will lead to mismatch for linear model and make the control scheme based on linear model invalid.

Table 1
Operating conditions of HIASCs with different product purities.

Purity	Low	Moderate	High
Nitrogen product purity	95.46%	98.41%	99.93415%
Oxygen product purity	96.13%	98.54%	99.907845%
Stage number	HPC:1–10 LPC:11–20	HPC:1–15 LPC:16–30	HPC:1–20 LPC:21–40
Feed stage	10	15	20
Feed composition (N_2, Ar, O_2)	0.78118, 0.00932, 0.2095	0.78118, 0.00932, 0.2095	0.78118, 0.00932, 0.2095
Feed pressure, Pa	579,573	579,573	579,573
Feed temperature, K	101.3	101.3	101.3
Feed flow rate, kmol/h	98.3	112.5	128.1
Feed thermal condition	0.26	0.26	0.26
Side stream stage	12	19	25
Side stream flow rate, kmol/h	12	14	17
Pressure of HPC, Pa	536,297	553,023	579,573
Pressure of LPC, Pa	163,584	146,281	115,718
Liquid holdup, kmol	1	1	1
$U_{ov}A$, W/K	9417	7789	6080

3.2. Sensitivity

Fig. 1 also shows the sensitivity of HIASC models with different purities. When disturbance occurs, the higher the purity is, the more sluggish the response is. The settling times of nitrogen product are around 1 h, 2 h and 7 h respectively when the purity increases. In HIASC, the heat integration between high pressure column and low pressure column leads to the sluggish response to disturbance, which is reinforced by the increasing purity. It means that the products of HIASC, especially for the high-purity model, are easily affected by disturbance but hardly to be controlled.

3.3. Asymmetry

Asymmetry is a distinct dynamic behavior, which refers to the situation, where the time required for a process to move from one steady state to another, depends on the direction of changes. TN1 and TN2 present the positive or negative transient times. So TN2/TN1 is used to describe the asymmetry degrees of the nitrogen product, and if TN2/TN1 becomes greater it means the differences between times required for different direction of changes become greater which also reveals that the asymmetric behavior become stronger. Fig. 2 shows nitrogen product responses of HIASCs with different purities when side stream flow rate of the Fifth LPC Tray first decreases by 10% and then backs to initial value. TN2/TN1 is 1.17, 1.62 and 3.88 respectively when the purity increases. So it is obvious that the degree of asymmetry for HIASC increases with increasing purity.

4. Nonlinear control scheme design based on wave model for HIASC with different purities

4.1. Derivation of shock wave velocity

In this section a concise and effective wave velocity for HIASC, called shock wave velocity, is derived. A nonlinear wave is defined as a spatial structure moving with constant propagation velocity and constant shape along a spatial coordinate, which is common dynamic phenomenon of separation processes and can be well used in the concentration description of HIASC. Shock wave velocity in this work chose the sharpest point on the profile as a representation of the front, and the derivation takes the material balance equations of HIASC into account.

The material balance equations of HIASC in previous work [43] can be written in an approximate expression as follows:

$$H^{*}\frac{\partial x_i}{\partial t}=\frac{\partial[(V+G)y_i]}{\partial Z}-\frac{\partial[(L+U)x_i]}{\partial Z}+\frac{\partial[Fz_i]}{\partial Z} \tag{1}$$

where $Z=\overline{Z}/\Delta Z$, ΔZ is the height equivalent to a theoretical plate, and $\overline{Z}$ represents the space coordinate of a certain position. After this transform, Z becomes a dimensionless variable that can describe a certain position of the HIASC, $H^{*}=H/\Delta Z$, which represents the liquid holdup per unit length.