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An advanced control of heat integrated air separation column based on simplified wave model

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ABSTRACT

An improved instant wave velocity is first derived for the heat integrated air separation column (HIASC), which is more simplified and accurate than the traditional one. Based on the simplified wave velocity, a nonlinear wave model of the high-purity HIASC is further established. Combined with the proposed wave model, a novel generalized generic model control scheme (SW-GGMC) is carried out, which is compared with the generic model controllers based on the traditional wave model (Wave-GMC) and data-driven model (Data-GMC), respectively. In both servo control and regulatory control, SW-GGMC exhibits the best performances. Detailed research results confirm the efficiency of the simplified wave model and the advantages of the proposed SW-GGMC control scheme.

1. Introduction

Quantities of high-purity industrial gas like nitrogen and oxygen are required in many important processes and industries like the Integrated Gasification Combined Cycle as well as the iron and the steel industry. Cryogenic air separation is a common method used for producing the industrial gases, however, it consumes large amount of energy [1–4]. Due to the high energy consumption, any improvement on the energy efficiency could produce a significant impact on the economic profit in the industry [5–8]. The heat integrated air separation column (HIASC) has 40% more energy-saving potential than the conventional air separation column (CASC), which are studied and confirmed by many researchers [9–13].

However, a high degree of thermal coupling and the high purity bring complex influences to the dynamic behaviors in the HIASC, such as the strong nonlinearity, the sensitivity to external disturbances and the asymmetry, which bring many difficulties for modeling and controller design [14–16]. Both the linear model and the traditional mechanism model have disadvantage for the HIASC. Although the linear model is simple, it cannot catch the nonlinearities of the HIASC well and it is an imprecise model. A traditional mechanism model is so complicated for a controller, because the variation of the production concentration is too small especially for the high-purity condition, which makes the mechanism model a computationally inefficient model [17–23]. So an advanced nonlinear model must be established which should be both precise and computationally efficient that contains the following characteristics: It must accurately describe the dynamics of the HIASC, and the structure must be simple enough for control design purposes.

The nonlinear wave theory, which proposes that the systems with distributed parameters often exhibit dynamic phenomena that resembles traveling waves [24–31], is well used by Luyben for distillation columns [32]. Marquardt et al. and Hwang et al. derived the expressions of the wave propagation velocity and studied the dynamic behaviors of the concentration waves, respectively [33–35]. Dunnebier et al. presented a simplified approach for the dynamic modeling of the chromatographic separation processes based on the model of the ideal chromatographic column, the thermodynamic equilibrium being described by the Langmuir isotherm, and the nonlinear wave

Abbreviations: C, compressor; CASC, conventional air separation column; Data-GMC, generic model control based on data-driven model; E, heat exchanger; GAIR, oxygen-rich vapor air; GGMC, generalized generic model control; GMC, generic model control; GN, nitrogen product; HIASC, heat integrated air separation column; HIDiC, heat integrated distillation column; HPC, high pressure column; ISE, integral square value of error; LAIR, oxygen-rich liquid air; LO, oxygen product; LPC, low pressure column; SW-GGMC, generalized generic model control based on simplified wave model; V, throttling valve; Wave-GMC, generic model control based on nonlinear wave model; WLN, side stream of low-purity liquid nitrogen product.

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Notation

Symbols

d	Disturbance input vector
F	Feed flow rate, kmol/h
f, g, h	Nonlinear relation
G	Gas side stream rate, kmol/h
H	Liquid holdup, kmol
K	Control parameter
L	Liquid flow rate, kmol/h
M	Weighting matrix
N	Number of the whole column stages
P_H	Pressure of high pressure column, Pa
q	Feed thermal condition
r	Relative order
S	Inflection point of wave profile
S^*	Inflection point under set point of the concentration
$\frac{dS}{dt}$	Wave velocity
t	Time, h
U	Liquid side stream rate, kmol/h
u	Manipulated variable vector
V	Vapor flow rate, kmol/h
X	Asymptotic limit when the profile extend to an infinite distance
x	Liquid mole fraction
$\hat{x}_{i,j}$	Estimation of liquid mole fraction
Y	System output
y	Vapor mole fraction
z	Feed mole fraction
α	State variable vector
β	Process parameter vector
γ	Tangent of the inflection point

Subscripts

h	High pressure column
i	a certain component of nitrogen, oxygen or argon
j	Stage number
l	Low pressure column

propagation [36]. Francis et al. designed a nonlinear model for a distillation column using the traveling waves which was able to capture certain inherent behavior [37]. The nonlinear wave propagation theory has been applied by Chern et al. to predict the breakthrough and the regeneration curves of the ion-exchange columns for the heavy metal removal [38]. The concept of coherence in the non-linear wave propagation was introduced by Helfferich et al. to describe a state in which the concentration velocities of all components present within a composition are equal [39]. Hsiaotao et al. showed that the constant-pattern wave model using the Langmuir isotherm equation could capture the dynamic behavior of the adsorption column [40]. 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 the HIDiC was established by combining a novel wave velocity with the thermal coupling relations and the material balance relations by Liu et al. [41]. Then Liu et al. developed a novel wave model based generic model controller of the HIDiC processes [42].

However, up to now there are few reports carried out for the control design based on the nonlinear wave model of the HIASC, which is more complex due to the high thermally coupled relations and the multicomponent non-ideal system that are different from both the HIDiC and the CASC. In previous work, a nonlinear wave model based on instant velocity of the HIASC was established [43]. But the instant velocity is complicated, which would impact the control performance. In the current work, an improved instant wave velocity is first derived for the HIASC, which is more simplified and accurate than the traditional one. Based on the simplified wave velocity, a nonlinear wave model of the high-purity HIASC is further established. In the proposed wave model of the HIASC, the inflection point of wave profile is chosen as the controlled variables based on wave theory, whose variation is large enough to be applied a controller. In previous work a generic model control (GMC) scheme was carried out for the HIASC [43,44]. In order to improve the control scheme, an expansion of GMC called generalized generic model control (GGMC) is proposed. GGMC inherits the advantages of GMC, for example, nonlinear process model can be directly used, controller parameters can be easily tuned and model mismatch can be compensated. Also, GGMC has its own advantages over GMC, for instance, GGMC can easily handle the nonlinear MIMO processes with relative order larger than one, and furthermore, the MIMO nonlinear processes can be naturally decoupled by GGMC [45–47]. So in the current work, combined with the proposed simplified wave model, a novel generalized generic model control scheme (SW-GGMC) is first carried out. The SW-GGMC is compared to a generic model controller based on the traditional wave model (Wave-GMC) and a generic model controller based on the data-driven model (Data-GMC) derived in a previous work [43]. In both servo control and regulatory control, SW-GGMC exhibits the best performance. Detailed research results confirm the accuracy and simplification of the simplified wave model and the advantages of the proposed SW-GGMC control scheme.