Nonlinear Reduced-Order Modeling of Double Column Air Separation Plants

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Abstract

Cryogenic air separation plants produce purified oxygen, nitrogen and argon for the steel, chemical, food processing, semiconductor and health care industries. Cryogenic temperatures (–170 to –190 °C) are achieved via turbine expansion. Electricity required to power gas turbines represents the largest operational cost in air separation plants. Continued deregulation of the electric utility industry is expected to result in frequent and unpredictable changes in the electricity costs. Linear model predictive control technology widely utilized in the air separation industry is not well suited for implementing large changes in plant operating conditions necessary to take advantage of time varying utility costs.

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We have been developing nonlinear modeling and control strategies that allow air separation plants to be transitioned over large operating regimes. Our previous work has focused on nonlinear wave modeling [5], compartmental modeling [2], state and parameter estimation [1] and nonlinear model predictive control [1] of nitrogen purification columns. This work was the first step towards developing effective control schemes for double and triple column plants more common in the air separation industry. This paper addresses the nonlinear modeling and control problem for double column plants used to produce nitrogen and oxygen products in both liquid and gaseous form. Given our previous contributions on the lower nitrogen purification column, the present work is focused on the upper column depicted in Figure 1. Novel aspects of this contribution include derivation of nonlinear reduced-order models from a first principles ternary model, integration of reduced-order models for the two tightly coupled columns and evaluation of the prospects for incorporating the combined reduced-order models in nonlinear model predictive control strategies.

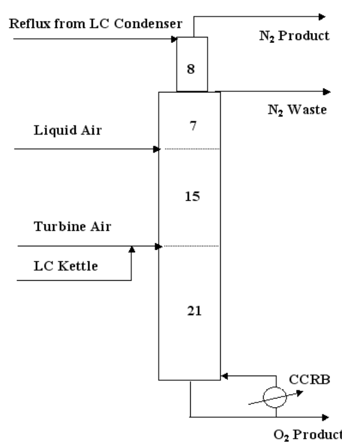

Figure 1: The upper column of a double column air separation plant.

A rigorous dynamic simulation of the double column plant constructed using Aspen Dynamics (Aspen Technology) is used to generate data for nonlinear model development and analysis. A first principles model of the upper column which includes stage-by-stage balances for liquid holdup, liquid phase enthalpy and vapor phase oxygen and argon compositions along with a detailed vapor-liquid equilibrium model is shown to provide good agreement with the Aspen simulator. The compartmentalization approach [4] is used to derive a reduced-order nonlinear model from the first principles model. Despite having substantially fewer differential state variables, the compartmental model is shown to accurately reproduce predictions generated by the first principles model.

A multicomponent extension [3] of nonlinear wave theory is used to develop a ternary wave model for the upper column. As a result of being considerably simpler, the wave model yields poor agreement with the first principles model. Nonlinear state and parameter estimation are shown to significantly improve wave model predictive capability. The upper column compartmental and wave models are combined with associated models for the lower column [2] through a detailed model of the combined reboiler/condenser system. The integrated reduced-order models are compared to the Aspen simulator for large changes in the air feed flow rate. These open-loop simulation results are used to assess the relative merits of each reduced-order model for nonlinear model predictive control for the double column plant.

References

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