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Dynamic modeling and explicit/multi-parametric MPC control of pressure swing adsorption systems

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ABSTRACT

Pressure swing adsorption (PSA) is a flexible, albeit complex gas separation system. Due to its inherent nonlinear nature and discontinuous operation, the design of a model based PSA controller, especially with varying operating conditions, is a challenging task. This work focuses on the design of an explicit/multi-parametric model predictive controller for a PSA system. Based on a system involving four adsorbent beds separating 70% H_2, 30% CH_4 mixture into high purity hydrogen, the key controller objective is to fast track H_2 purity to a set point value of 99.99%. To perform this task, a rigorous and systematic framework is employed. First, a high fidelity detailed dynamic model is built to represent the system's real operation, and understand its dynamic behavior. The model is then used to derive appropriate linear models by applying suitable system identification techniques. For the reduced models, a model predictive control (MPC) step is formulated, where latest developments in multi-parametric programming and control are applied to derive a novel explicit MPC controller. To test the performance of the designed controller, closed loop simulations are performed where the dynamic model is used as the virtual plant. Comparison studies of the derived explicit MPC controller are also performed with conventional PID controllers.

1. Introduction

Pressure swing adsorption (PSA) is one of the unit operations where invention occurred before the underlying theories behind it were fully understood. Since its commercial inception in late 1950s, PSA technology has evidenced substantial growth in terms of size, versatility and complexity [25,35]. Modern PSA systems, used widely in the gas separation industry can vary from 2 adsorbent bed separating air, to 16 bed system producing pure hydrogen in excess of 100,000 N m^3/h [33]. PSA operation is not only highly nonlinear and dynamic but also poses extra challenges due to its periodic nature; directly attributed to the network of bed interconnecting valves whose active status keeps changing over time. The timing of these valves in turn control the duration of process steps that each PSA bed undergoes in one cycle. In the past, only a few studies have appeared in the open literature on PSA control even though there is an increasing interest to improve their operability [29]. Bitzer [2] presented model based feedforward-feedback purity control of a 4-step, 2-bed PSA system producing oxygen from air. Since the original model used to capture the PSA system was not suitable for the feedforward controller purposes, a reduced model was derived by approximating the species axial concentration profiles through empirical wave functions. However, the applicability of this key assumption for more complex and realistic PSA system has not been fully demonstrated. Torre et al. [28] proposed a model predictive control (MPC) for purity control of a 6-step, single-bed vacuum swing adsorption configuration, separating oxygen from air.

MPC seems to be an appropriate control methodology for these highly complex, interconnected dynamic systems. In contrast to a standard PID controller, MPC provides optimal control action by taking into account system's dynamic behavior and operational constraints [12,20–22]. It is based on receding horizon philosophy, where the current plant state and output variables, along with a suitable plant model are utilized to calculate the future sequence of optimal input variables. MPC control law, is therefore implicit in nature and requires repeated *online* solution of the optimization problem, as state of the plant evolves in time. On the other hand, recent advances made in the field of multi-parametric programming now makes it possible to obtain the governing MPC control law beforehand, or *offline*. Pistikopoulos et al. [17], first demonstrated this by employing multi-parametric techniques to reformulate the original MPC problem into a multi-parametric optimization problem, wherein the dynamic state and output variables are treated as varying parameters. Following this approach, the resulting control laws obtained are explicit functions of the defined parametric set and can be stored for later use. Consequently, the online work is now reduced to performing

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