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Dynamic analysis and control of sieve tray gas absorption column using MATALB and SIMULINK

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ABSTRACT

The present work highlights the powerful combination of SIMULINK/MATLAB software as an effective flowsheeting tool which was used to simulate steady state, open and closed loop dynamics of a sieve tray gas absorption column. A complete mathematical model, which consists of a system of differential and algebraic equations was developed. The S-Functions were used to build user defined blocks for steady state and dynamic column models which were programmed using MATLAB and SIMULINK flowsheeting environment. As a case study, the dynamic behaviour and control of a sieve tray column to absorb ethanol from CO_2 stream in a fermentation process were analysed. The linear difference equation relating the actual and equilibrium gas phase compositions was solved analytically to relate the actual gas phase composition to the liquid phase with Murphree tray efficiency as a parameter. The steady state mathematical model was found to be nonlinear (w.r.t. number of stages) due to the introduction of the Murphree tray efficiency. To avoid the solution of large linear algebraic system, a sequential steady state solution algorithm was developed and tested through the idea of tearing the recycle stream in the closed loop configuration. The number of iterations needed to achieve a given tolerance was found to be function of the Murphree tray efficiency. The open-loop dynamic analysis showed that the gas phase composition response was nonlinear with respect to the inlet gas flow rate, while it was linear with respect to inlet gas composition. The nonlinearity increased along the column height and was maximum at the top tray. On the other hand, the Murphree tray efficiency had little effect on the dynamic behaviour of the column. The controlled variable was found to exhibit fairly large overshoots due to step change in the inlet gas flow rate, while the PID controller performance was satisfactory for step change in the inlet gas composition. The closed-loop dynamic analysis showed that the controlled variable (outlet gas phase composition) had a fairly linear dynamics due to step changes in the set point.

1. Introduction

Steady state design of chemical equipment is confronted by dynamic and controllability issues. In this regard, it is often easy to design a chemical process based on steady state conditions, which is practically uncontrollable and unrealistic. In order to avoid any wrong assumption during process synthesis and design, and to ensure safe start-up, shutdown and stable plant operation, the dynamic behaviour of the relevant units should be known. Dynamic simulation is known to be a slow process, in particular when used on the flowsheet level, where the challenge is dealing with processing units having different time constants. However, dynamic simulation makes use of recent advances in computers power in terms of memory and computational speed, and the advances in information technology where user friendly GUI and flowsheeting packages are used intensively [1,2,21,28,29]. Kvamsdal et al. [2] presented three important factors, which contribute to the importance of the dynamic simulation to improve the overall design and optimize the operation of chemical processing units. These factors are: (1) the coupled absorber/stripper system is complex, with higher degree of two-way interaction between these two units. (2) The upstream processing units might operate under a varying load operation. (3) New process approaches, with energy integration mean more complex operations. Therefore, a dynamic process simulator enables the study of most of these isolated or coupled effects.

The dynamic simulation and control of gas absorption process attracted many researchers' attention on both individual and flowsheet (planwide) levels [2,3,28,29]. Kvamsdal et al. [2] presented a dynamic model of a CO_2 absorption column that is intended to

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Nomenclature

A_P	active plate area (m^2)
b	slope of equilibrium curve
c	weir constant ($m^{1/2}\ s^{-1}$)
G	gas flow rate (mol/s)
G_c	industrial PID controller transfer function (psig)
h_w	weir height (m)
K	equilibrium constant
K_c	controller gain
K_p	process gain (s/mol)
L_0	absorbent inlet flow rate (mol/s)
L_w	weir length (m)
L_j	liquid flow rate from the jth tray (mol/s)
M_j	total liquid holdup on jth tray (kmol)
M_0	steady state liquid holdup on each tray (kmol)
N	number of trays
P	column operating pressure (atm)
T	column operating temperature (°C)
t	time (s)
x_{in}, y_{in}	solute mole fraction in the inlet absorbent and gas stream respectively
x	steady state mole fraction of solute concentration in the liquid phase
x_j	mole fraction of solute in the liquid phase
y_j^*	is the equilibrium solute mole fraction in the gas phase leaving stage j
y_j	mole fraction of solute in the gas phase leaving stage j

Greek symbols

α	parameter introduced to realize the controller transfer function
τ_I, τ_D	integral and derivative actions respectively (s)
η	Murphree tray efficiency
ρ_L	molar density of the liquid mixture (mol/m^3)

be coupled with models of other individual processes to form a complete model of a power generation plant with CO_2 removal. In their model, the operational challenges, such as load variation and high degree of heat integration between the power plant and the absorber/stripper process were studied. Lin et al. [3] presented planwide control of a reactive CO_2 absorption/stripping process with monoethanol-amine as a solvent using dynamic simulation. These authors proposed a new control structure, where the liquid absorbent flow rate (at the top of the column), the liquid level and temperature at the bottom of the stripping column were controlled. Through the help of dynamic simulations, the developed model and control structure was found to achieve removal targets and stabilize quickly under the influence of external disturbances.

Robinson and Luyben [28,29] presented a hybrid power/chemical plant model for the purpose of dynamic simulation and planwide control structure design. This hybrid power/chemical plant is the gasification process producing synthesis gas, which under standard operation conditions feed a combustion turbine to generate electricity or feed a chemical plant during periods of lower power demand. These authors used process simulator ASPEN to perform dynamic simulations of the H_2S and CO_2 absorption/stripping processes and water–gas shift reactors, which are essential for the development of stable and robust plantwide control structures of this hybrid plant.

From the above review, it is obvious that dynamic simulation and control of gas absorption process is essential. Moreover, it is clear that gas absorption/stripping is one of the main and important processing blocks in many chemical and power generation plants. It is used in pollution control devices such as wet scrubbers and spray-dryer-type, dry scrubbers for the removal of acid gas compounds and water-soluble organic compounds [4,5]. This process is usually carried out through tray columns that contain multiple numbers of trays, which bring gas and liquid into intimate contact. If the gas leaving the tray is in thermodynamic equilibrium (which is a rather rare situation) with the liquid leaving the tray, then theoretical stage is provided. To account for the failure to achieve equilibrium, Murphree tray efficiency is used. The computational approach is to determine the theoretical stages and then correct to actual stages by means of tray efficiency [6]. The use of the component Murphree tray efficiency for separation of binary mixtures has been described by several authors: Hines and Maddox [7], Van Winkle [8], Edmister [9] and Holland and McMahon [10]. However, a simple way to apply Murphree tray efficiency to liquid–vapour separation processes has not been shown. Edmister [9] presented a description of different types and uses of tray efficiencies. A tray efficiency was defined as a multiplier of the absorption or stripping factor on each stage. Takamatsu and Kinoshita [11] showed a new solution process for multi-component distillation columns. They took the liquid mole fractions to be the independent variables and their difference between consecutive iterations to be the functions set to zero. Their procedure seems to be stable and fast, and the application of the Murphree efficiency includes a new step in solving the liquid–vapor composition non-equilibrium equations with a successive substitution method. In general, the values of the Murphree tray efficiencies are not equal throughout the column. Further, they usually are not equal for the different components in a mixture, even on the same stage.

The gas absorption process is modelled through a system of mathematical equations to enable prediction of the process behaviour [12]. These equations do not have a general analytical solution and some approximations and numerical methods can be used for solving them [13]. The implementation of a control scheme for such a process is vital to achieve optimal operation despite the presence of significant uncertainty about the plant behaviour and disturbances. The purpose of any control system is to suppress the influence of external disturbances, ensure the stability of process and optimize process performance. The feedback system is a common control configuration where it uses direct measurements of the controlled variables to adjust the values of the manipulated variables. The objective is to keep the controlled variables at desired levels (set points) [14,15]. There are various controllers that can be considered for implementation such as: proportional–integral–derivative (PID) controller and Artificial Neural Networks (ANN) controller [16]. As the capability of a certain controller is not the main issue of the present work, the traditional PID controller was selected for its simplicity when compared with ANN and being able to achieve the required targets. Tuning the PID feedback controllers is the adjustment of the controller parameters to match the characteristics of the rest of the components of the loop. One of the popular methods is the on-line or closed-loop tuning method. For the desired response of the closed loop, Ziegler and Nichols specified a decay ratio of one-fourth. The decay ratio is the ratio of the amplitudes of two successive oscillations ([17,18]).

MATLAB is a software for mathematical computation, whereas SIMULINK is a powerful software for modelling, simulation, and analysis of dynamical systems in a flowsheeting environment. It supports linear and nonlinear systems, modelled in continuous time, sampled time, or a hybrid of the two. Bequette [19], illustrated that the interactive MATLAB/SIMULINK tool enhances the ability to learn new model-based techniques and provide an inside depth of the dynamic nature and control of chemical processes [20]. For modelling, SIMULINK provides a graphical user interface (GUI) for building models as block diagrams, using click-and-drag mouse