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Multivariate monitoring of a carbon dioxide removal process

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ABSTRACT

Process hardware improvements have significantly increased the amount of information collected in industrial facilities, which allows the use of tools such as multivariable statistical analysis for process monitoring. Nevertheless, such statistical models tend to be static and extremely general when implemented in process facilities with several modes of operation, as is the case of carbon dioxide removal processes. This work demonstrates the use of multivariable statistical analysis for process transitions between different modes of operation. Continuous process analytics are used to define key variables, named "state variables", to determine the current mode of operation. This work also makes use of parallel coordinates to illustrate the simultaneous visualization of several transition paths and statistical tests. Such tests apply confidence limits that are appropriate to the current mode of operation. This methodology is successfully tested in the CO_2 capture plant at the University of Texas in Austin. The results show the effectiveness of using this type of application to detect abnormal operating conditions at different levels of operations.

1. Introduction

Significant advances in process control hardware have provided an extensive source of information to determine current conditions in chemical plants in view of maintaining optimal operations with minimal costs. The number of signals available in plant operations has increased in the past decade as sensors are connected to a common network and measurements can be obtained from different locations of an industrial complex. All this information is also stored so that many data driven statistics are withdrawn from the data historian. This tremendous supply of information is made available in fractions of a second to processors equipped with software capable of sophisticated graphical functionality and statistical calculations, which enables control engineers to seek better operational performance.

Process monitoring is an effective way to initiate advanced control applications as data are analyzed and incorporated in a statistical model without applying drastic changes in the process. The first statistical techniques were based on univariate process analysis, where variables are independently analyzed from each other (Harris, Seppala, & Desborough, 1999; Howarth, 1995). The explosion of sensor measurements opened the possibility to apply multivariable approaches for process monitoring in industrial facilities (Kano & Nakagawa, 2006; Kourti, 2005). The main principle consists of compressing data, due to process measurement correlations, into a few empirical variables capable of tracking of most of the process data variance (Macgregor & Kourti, 1995).

The importance of having reliable process monitoring systems supervising production facilities comes from the need of assuring reliable operations and optimal productivity based on process instrumentation observations, probability distributions and statistical analysis. Statistical process monitoring provides the tools to prevent major impacts of abnormal conditions if the process is in a healthy state.

Many of the graphical charts used in this work are new in the literature but powerful to apply these types of techniques. The capacity to synthesize and illustrate operating conditions in a convenient graphical representation is important for industry. One of the objectives of this work is to demonstrate a friendly user interface environment using a unique graphical representation.

This work arose from the study of carbon dioxide removal from power plant exhaust gases. Besides the current interest in removing and reducing contaminants from the environment, CO_2 capture processes operate over a wide set of conditions due to changes in power plant loads and energy prices (Riemer, 1996). The coupling between liquid and gas flows through the absorption and stripper columns in this type of processes demonstrates the importance of data correlation in the monitoring of such facilities. Therefore it is of great importance to present a complete methodology of implementing process monitoring to further reduce the costs of operating faults in CO_2 capture facilities.

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Section 2 of this paper describes the CO_2 removal process and highlights the decision variables that permit the plant to operate in different modes. Section 3 introduces important process monitoring tools like principal component analysis, parallel coordinates and continuous process analytics. The notions of clustering, modes of operation and transition profiles are presented in Section 4. Such concepts permit the use of adjustable parameters for a plant with a broad range of operation. Section 5 presents the implementation of multivariable statistical process monitoring for CO_2 capture processes, visualized in parallel coordinate plots. Conclusions are provided in Section 6.

2. Process description

The picture shown in Fig. 1 illustrates the research facility used for the CO_2 recovery pilot plant in the separations research center at the University of Texas in Austin. This plant consists of absorption and stripping columns with 35 wt% aqueous monoethanolamine (MEA). MEA is the most common solvent for small CO_2 recovery plants.

The main process equipment is depicted in the flow sheet of Fig. 2. This flow sheet shows that purified gas with low CO_2 leaves the top of the absorber column to the atmosphere. The absorber receives typical coal-fired flue gas containing 10–12% CO_2 at 40–60 °C and at atmospheric pressure. The lean CO_2 solvent is introduced to the absorber with a CO_2 loading of 0.1– 0.2 mol/mol MEA. The rich CO_2 solvent leaves the bottom of the absorber with 0.4–0.5 mol CO_2/mol MEA. An inter-cooler is occasionally used to improve absorption at the absorber midsection.

Fig. 1. CO_2 recovery process pilot plant at the University of Texas in Austin.

This pilot plant recycles the CO_2 removed in the stripper (left column) while keeping constant the concentration of CO_2 in the flue gas fed to the absorber. Makeup CO_2 is used at startup conditions and to reduce CO_2 variations in the gas recycle stream. The stripper column removes the CO_2 from the rich loading stream by increasing the temperature to about 120 °C at the bottom. The stripper operates between 1.5 and 2.0 atm and steam is used at the reboiler to heat the aqueous solution. The lean loading flow of the stripper bottom product preheats the rich loading feed to the stripper in order to reduce the steam consumption in the reboiler. Such a scheme optimizes energy used for CO_2 recovery at the expense of increasing operational interactions.

For a given equipment configuration there are four top level decision variables that define the operating conditions of this pilot plant. These variables are manipulated or considered as input disturbances to the process. A brief explanation of their significance and effect in CO_2 capture is provided next.

- *Flue gas load*: the gas load depends on the amount of fuel consumed, which is proportional to the electric power generated. An actuator adjusts the amount of flue gas diverted for CO_2 recovery to reduce the impact of this disturbance on the CO_2 removal plant operations. In some cases the actuator keeps the damper in full-open position to maximize the amount of flue gas treated. The U.T. pilot plant recirculates the gas from the top of the stripper to the absorber. The flue gas CO_2 concentration is adjusted to 12% by the CO_2 makeup gas flow. A variable speed air blower is used to regulate the flue gas flow delivered to the absorber.
- *Solvent flow circulation*: the solvent flow rate is adjusted by variable speed pumps throughout the whole plant while maintaining liquid inventories at the different plant locations. Changes in the liquid circulation affect the process time constant and the dynamic response. Larger circulations decrease the plant response time. At the same time large liquid flows increase energy consumption, especially at the stripper reboiler. Although solvent flow to the absorber and stripper might be momentarily decoupled by the solvent inventory tank, their trends are correlated because tank levels are controlled.
- *Stripper pressure*: the stripper pressure is regulated by the amount of gas removed from the rich loading stream. An exhaust valve can be used to control the pressure in the stripper between 1.5 and 2 atm to minimize amine degradation (Plaza, Van Wagener, & Rochelle, 2009). Recent studies indicate that leaving the control valve fully open reduces the reboiler heat duty and increases the efficiency of the process (Ziaii, Rochelle, & Edgar, 2009). Therefore, although a pressure control valve is installed at the top of the stripper, the pressure may swing depending on the amount of CO_2 absorbed as well as the column temperature changes.
- *Reboiler steam flow*: the steam flow regulates the temperature in the stripper bottom and the amount of CO_2 removed from the solvent. The rich and lean span in CO_2 concentration depends on the solvent flow and reboiler heat. A goal of 90% CO_2 removal is achieved at high steam consumption. However, high steam consumption is detrimental to the power plant efficiency, as about 30% of low pressure steam available in the power plant is consumed in the reboiler.

Fig. 3 illustrates the trends of process decision variables. The sudden change of some of these variables demonstrates that modes of operation can be defined based on key decision variables. This pilot process incorporates more than a hundred sensors that could be used to detect abnormal operating conditions at different levels of operation. The following sections demonstrate the tools and