INTERNATIONAL JOURNAL OF ADAPTIVE CONTROL AND SIGNAL PROCESSING
Int. J. Adapt. Control Signal Process. (2012)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/acs.2282

Adaptive predictive control of the sulfur recovery process at Pemex Cadereyta refinery

Angelo Raimondi [1,*,†], Antonio Favela [1], Raul Estrada [1], Antonio Nevado [2] and Edgar Gracia [3]

[1] *Department of Mechatronics and Automation, ITESM - Campus Monterrey, Monterrey, Mexico*
[2] *UNED/DIEEC, Juan del Rosal 12, 28040 Madrid, Spain*
[3] *"Ing. Hector R. Lara Sosa", Pemex Refinery, Cadereyta, NL, Mexico*

SUMMARY

This paper describes the design and application of an optimized control system, based on adaptive predictive expert control methodology, to the sulfur recovery units (SRUs) of the Pemex Refinery in Cadereyta, and presents comparative results obtained in relation to those of the conventional control system operating the plant. The sulfur recovery process represents the final stage in the refinery production chain, and is responsible for removing the sulfur content, usually in the form of hydrogen sulfide (H_2S) waste gas generated by other refinery processes. The main goal is minimizing the sulfur content in the gasses released into the atmosphere to comply with emission level requirements. This goal can be obtained by a precise control of the ratio between hydrogen sulfide and sulfur dioxide (SO_2) in the tail gas, which determines, through a Claus reaction, the maximum sulfur recovery. The SRUs operating in Cadereyta were connected to a common amine acid gas collector and a common ammonia acid gas collector. Optimized control strategies were designed to control the pressure on both acid gas collectors and the flow rate of air entering each SRU. The results show that the $H_2S : SO_2$ ratio in the tail gas is considerably more stable under optimized control, particularly in the presence of abrupt changes in the acid gas load. The peaks observed in this ratio under conventional control disappear under optimized control showing a significant improvement in the process operation. Copyright © 2012 John Wiley & Sons, Ltd.

Received 3 August 2011; Revised 17 January 2012; Accepted 25 January 2012

KEY WORDS: adaptive control; predictive control; ADEX control; sulfur recovery; Claus process

1. INTRODUCTION

Since the beginning of automation in petrochemical plants, PID controllers have been the standard tool for basic automatic control of generic variables such as flow rates, levels, pressures or temperatures [1, 2]. However, the simple application of this basic controller can only provide a limited solution to the control problems faced in the operation of many industrial plants. Advanced control was initially introduced as a more sophisticated type of solution that combined the use of PID controllers with appropriate control strategies based on specialized knowledge of plant dynamics. This first generation of advanced control has been, and continues to be, extensively used in the petrochemical field and has proved to be of great help in the operation of petrochemical plant [2–4].

The principles of predictive and adaptive predictive control were introduced in the late seventies [5–8] and during more than three decades, research and publications in this field have

*Correspondence to: Angelo Raimondi, Department of Mechatronics and Automation, ITESM - Campus Monterrey. Ave. Eugenio Garza Sada 2501 Sur, Col. Tecnológico C.P. 64849, Monterrey, Nuevo León, México.

†E-mail: araimondi.mty@itesm.mx

been maintained at a high level. In the context of predictive control without adaptation, where the model must be obtained prior to the control application, several alternatives were proposed [9–12] and are currently being used commercially, mainly in the petrochemical industry. Most reported advanced control applications in oil refining industry are mainly related to Model Predictive Control techniques [13–17], but there are also reported applications related to Expert Systems [18].

However, the performance of predictive control with a fixed parameter model may deteriorate when process parameters change, and a model mismatch is produced. Thus, adaptive predictive control (APC) appeared as a solution theoretically able to make a better approach to the inherent time-varying nature of process dynamics. This was first illustrated by the application of APC to the multivariable control of a binary distillation column carried out in 1976 [5, 19]. Other applications of APC were later on successfully applied in a variety of plants [20–24] outside the petrochemical industry.

This paper describes the implementation of a control system, based on adaptive predictive expert (ADEX[‡]) control methodology, to the sulfur recovery process at the Pemex Refinery of Cadereyta (Mexico). The ADEX methodology [25, 26] is an extension of APC that enables available plant knowledge to be used within the controller by means of an additional expert component. Within the petrochemical industry, it was first applied to several processes at the Repsol Escombreras refinery [26], and later in a naphtha splitter at the Repsol Puertollano refinery [27].

The sulfur recovery process represents the final stage in the refinery production chain and is responsible for removing the sulfur content, usually in the form of hydrogen sulfide (H_2S), from waste acid gas generated by other refinery processes. The main goal is minimizing the sulfur content in the gasses released into the atmosphere to comply with emission level requirements.

The sulfur recovery units (SRUs) operating in Cadereyta are connected to a common amine acid gas collector and a common ammonia acid gas collector. Precise control of the air supplied to each SRU can determine the maximum sulfur recovery. When an appropriate ratio of hydrogen sulfide is converted into sulfur dioxide (SO_2) by the air supplied, a Claus reaction optimizes the SRU performance. However, these SRUs involve complex, multivariable, interactive, non-linear and time-varying processes that are normally subjected to continuous and even drastic changes in the load of acid gasses to be treated during the operation. The existing conventional PID control system resulted in undesirable oscillations of the SRU critical variables, and the need for improved control performance prompted the ADEX system application. No previous report of advanced control application to this kind of process has been found in literature.

The ADEX system was implemented at the SRUs of the Cadereyta refinery by using ADEX control and optimization platform (ADEX COP), a control and optimization software platform [26] that allows the design, development and application of control strategies where ADEX controllers are integrated. The objective of the ADEX system application was to stabilize the ratio $H_2S:SO_2$ in the tail gas of the SRUs around the value of 2, which makes the Claus process reach its maximum recovery efficiency around 98%, also because of the use of the tail gas treatment units (TGTU) that enables enhanced sulfur recovery when the SRUs operate in stable conditions.

Section 2 of this paper presents a description of the sulfur recovery process at the Pemex Cadereyta refinery, including the plant layout, the Claus reaction within the SRU, the control challenges and the previous control system operating the plant. Section 3 presents the basic concepts of ADEX methodology, the ADEX COP used to implement the ADEX system, and the architecture that allowed the input/output (I/O) communication between ADEX COP and the SRUs. The optimized control strategies, designed to control the pressure on both acid gas collectors and the flow rate of air entering each SRU, are presented in Section 4. Section 5 presents the field results obtained by the ADEX system and performs a comparative analysis of them in relation to those of the previous PID based control system. The conclusions are drawn in Section 6.

[‡]ADEX is a trademark of Adaptive Predictive Expert Control ADEX S.L.

DOI: 10.1002/acs

2. PROCESS DESCRIPTION

2.1. Claus process

Operation of the sulfur recovery process is based on the Claus process, which consists of a thermal stage and a catalytic stage. In the thermal stage, hydrogen sulfide acid gas reacts under stoichiometric combustion at a temperature above 850 °C such that elemental sulfur precipitates in a downstream process gas cooler. In the thermal stage, acid gas is mixed with other combustible components, such as hydrocarbons or ammonia, and is burnt in accordance with the following chemical reaction:

$$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O \tag{1}$$

This is a strongly exothermic free-flame total oxidation of hydrogen sulfide generating sulfur dioxide that reacts away in subsequent reactions. The most important one is the Claus reaction:

$$2H_2S + SO_2 \rightarrow 3S + 2H_2O \tag{2}$$

The overall equation is as follows:

$$10H_2S + 5O_2 \rightarrow 2H_2S + SO_2 + \frac{7}{2}S_2 + 8H_2O \tag{3}$$

showing that in the thermal step alone, two-thirds of the hydrogen sulfide is converted to sulfur.

Gasses containing ammonia, such as the gas from the refinery's sour water stripper, or hydrocarbons, are also converted in the reaction furnace. Sufficient air must be injected into the reaction furnace for the complete combustion of all hydrocarbons and ammonia. Thus, the air necessary to maintain the $H_2S : SO_2$ ratio must be controlled such that in total, $\frac{1}{3}$ of all hydrogen sulfide (H_2S) is converted to SO_2. This ensures the stoichiometric balance necessary for the best Claus reaction in the catalytic stage.

In this stage, the Claus process continues with activated aluminum or titanium oxide, and serves to boost the sulfur yield. More hydrogen sulfide (H_2S) reacts with the SO_2 formed during combustion in the reaction furnace of the Claus reaction, and results in gaseous, elemental sulfur as shown below.

$$2H_2S + SO_2 \rightarrow 3S + 2H_2O \tag{4}$$

The tail gas from the Claus process still containing combustible components and sulfur compounds (H_2S, H_2 and CO) is either burned in an incineration unit or further desulfurized in a downstream TGTU.

2.2. Plant layout

Figure 1 shows the functional diagram of the Cadereyta refinery sulfur recovery process. The main function of the Refinery SRUs is to extract raw sulfur from hydrogen sulfide H_2S in the acid gas streams emanating from the contributing plants concentrated in two headers, the first one in the form of amine acid gas, and the second, in the form of ammonia acid gas, which does not enter SRU 1. In the amine acid gas header, gas streams from the Hydro-desulfurization plants 1 and 2 commingle with catalytic plants 1 and 2 and hydro-diesel. In addition, streams from the sour water exhaust columns reach ammonia acid gas headers 5, 6, 7 and 8.

The SRUs comprise a reactor burner, where hydrogen sulfide is burned in the presence of air. The air is fed through a combination of blowers, one for SRU 1, three common blowers for SRUs 3 and 4, and another three for SRUs 5 and 6. The air intake at each reactor burner is controlled by means of a two-valve system (coarse and fine air control). Inside the burners, temperatures of 1100 °C are reached, and the heat from the burner outlet gas is used for heating a connected boiler. At the outlet from the boiler, the temperature is around 380 °C. Subsequently, the tail gas goes through three condensation phases where raw sulfur is recovered. At the end of the condensation phases, a tail gas

DOI: 10.1002/acs

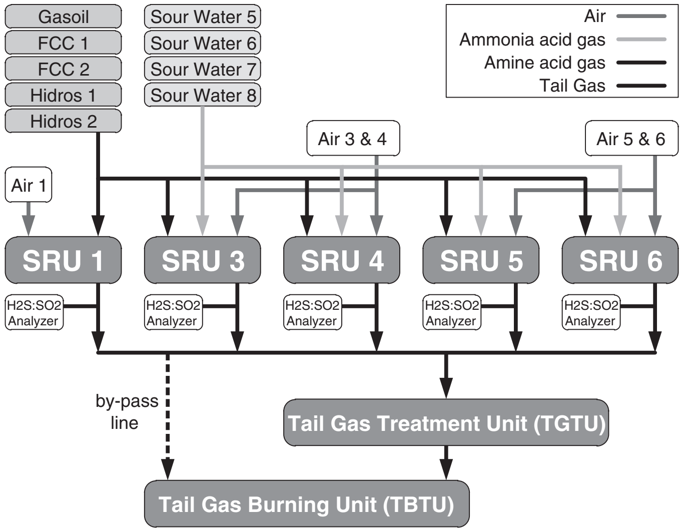

Figure 1. Functional diagram of the Cadereyta refinery sulfur recovery process.

analyzer is located for measuring the H_2S and SO_2 content and the reaction air demand, which is a measure of the $H_2S : SO_2$ ratio. This last value is the most important variable of the process.

The flow emanating from the condensation phase can be directed towards the TGTU enabling optimum levels of sulfur recovery. In addition, in the event that operating conditions do not permit, the tail gas flow is by-passed directly to the incineration burner (TGBU) and vented.

2.3. *Control challenges*

The sulfur recovery process presents the following significant control challenges:

- Since acid gas streams are influenced by the operation of many different processes, the total volume of acid gas and the content of H_2S within these streams are highly variable;
- There is a significant time delay between the control action on the air flow rate of each SRU and the measurement of $H_2S : SO_2$ ratio, which is taken by the air demand analyzer at the end of the catalytic stage (tail gas);
- Because of the common feeding headers, flow changes in one SRU affect all the rest by means of the header pressure;
- A two-valve system (coarse and fine air) delivers total air flow, which is the only independent means of controlling the process, but the coarse air valve shows a highly non-linear behavior;
- The nature of both exothermic and catalytic reactions are characterized by a high-order, non-linear and time varying dynamic.

2.4. *Previous control system*

The conventional control strategy aims at maintaining a suitable ratio between the treated acid gas flow and air demand in order to oxidize the hydrocarbons and H_2S, achieving a zero reading, approximately, in the air demand analyzer (ADA), resulting in a Claus reaction (2) to be balanced before entering the catalytic stage.

To achieve this balanced condition, the flow rates of acid gas and air entering the reaction furnace are under PID control. The flow rate of air demand is regulated by means of valves in two parallel air lines located in the drive of the blowers. One valve, which is smaller and more accurate, is controlled in cascade with the air demand signal sent by the tail gas analyzer, whereas the second larger valve is normally manually controlled by the operator.

DOI: 10.1002/acs

Although it is possible to operate by controlling pressure in the acid gas lines at each of the SRU inlets, this method was not normally used. A further option of controlling the coarse air valve in cascade with the ADA was not used either.

3. IMPLEMENTATION OF THE ADAPTIVE PREDICTIVE EXPERT CONTROL SYSTEM

3.1. Adaptive predictive expert control methodology

The methodology of ADEX [25, 26] arises from the integration of APC [5, 7, 22] and expert control [28], defining domains of operation for each of them in an integrated structure of control. ADEX methodology enables the controller to be designed in such a way that it detects its current operating domain and uses the best information available from the process to apply adaptive predictive control (AP domain) or expert control (EX domain) accordingly. ADEX control benefits from the experience of the operator and defines the rules governing the use of expert control or the best way of applying AP control in each domain of operation. In this way, ADEX overcomes the lack of robustness of APC and can be used to apply optimized control as explained in the following.

Expert control is applied in operating domains, where the basic objective is to lead the process variables back towards domains, where the application of APC is possible and desirable. APC in these AP domains quickly reduces the prediction error towards zero, which enables the evolution of the process variables to be guided in the desired way, solely with the logical restriction of the physical limitations of the process itself.

In this way, the criterion for the design of the desired evolution of the process variables does not depend on stability considerations, as in the typical case of control systems based on PID controllers, but will be able to focus on the objective of optimizing the performance of the process, without any other restriction other than physical limitations. Obviously, reaching the objective of optimized control entails the correct selection of the criteria for the design of the desired evolution of the process variables, and generally, this selection is made by applying ADEX controllers in the context of strategies that respond to the optimization criteria.

3.2. Control and optimization platform

The ADEX COP [25, 26, 29] used in the implementation of the ADEX system of this project, to enable the development and application of optimized control strategies (OCS) acting in parallel to (on top of) the already installed system (local system) that controls the process. Also, it incorporates the ability to simulate processes and to supervise the OCS in operation. ADEX COP uses LabView[§] as the graphical integrated development environment (IDE) for the implementation of OCS.

The basic structure of ADEX COP is shown in Figure 2. It includes a supervisory and configuration system (ADEX SCS) and a control and optimization system (ADEX COS). ADEX SCS allows the following:

1. Development of the OCS by means of a GUI that uses ADEX controllers and logic operators stored in the ADEX COS memory;
2. Configuration of ADEX controllers.

Also, Figure 2 represents schematically the implementation of an OCS, which is described, in the following steps for every control instant:

(a) Acquisition of the process variables relevant to optimization via OPC from the local control system;
(b) Execution of the OCS capable of calculating the optimized control signals;
(c) Transfer via OPC of the optimized control signals to the local system, so that they can be applied to the process;
(d) In event of an OPC communication failure, use of a locking logic that allows the local control system to manage the process.

[§]LabView is a trademark of National Instruments.

DOI: 10.1002/acs

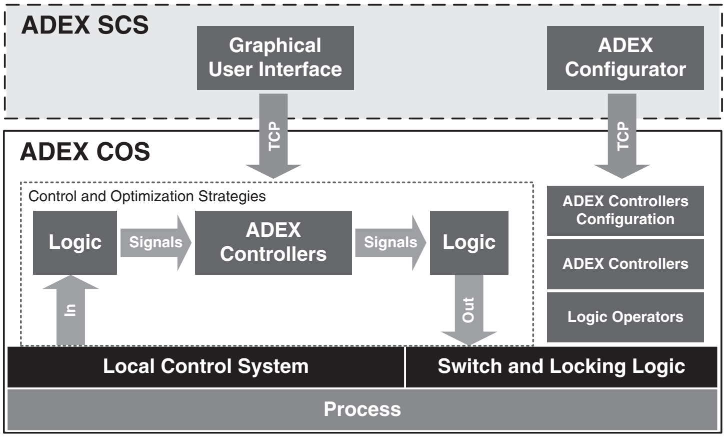

Figure 2. Basic structure of adaptive predictive expert and optimization platform.

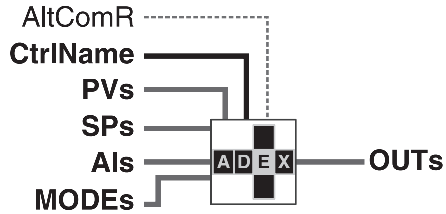

Figure 3. Adaptive predictive expert controller graphical operator.

3.3. *Adaptive predictive expert controllers*

As previously mentioned, ADEX COP allows ADEX controllers to be created and integrated in the OCS, where they are represented by graphical operators shown in Figure 3.

The ADEX controllers are designed to be multivariable, which means that the inputs, that is, process output (PVs), setpoint (SPs), and outputs (OUTs) are vectors. Also, the controller receives the information of the actual input (AIs) vector applied to the process in the previous control instant, the mode (MODEs) of operation, the controller name (CtrlName) and a signal (AltComR) indicating that the OPC communication with the local system is functioning correctly.

When the ADEX controller operates in an AP domain, it uses an incremental AP model to calculate an a priori estimation of the process output and predicts, at control instant k, the process output by means of equations of the form:

$$\hat{Y}(k|k-1) = \sum_{i=1}^{h} \hat{A}_i(k-1)Y(k-i-r) + \sum_{i=1}^{f} \hat{B}_i(k-1)U(k-i-r) + \sum_{i=1}^{g} \hat{C}_i(k-1)W(k-i-r) \quad (5)$$

$$\hat{Y}(k+r+1|k) = \sum_{i=1}^{h} \hat{A}_i(k)Y(k-i+1) + \sum_{i=1}^{f} \hat{B}_i(k)U(k-i+1) + \sum_{i=1}^{g} \hat{C}_i(k)W(k-i+1) \quad (6)$$

DOI: 10.1002/acs

where $Y(k-i-r)$, $U(k-i-r)$ and $W(k-i-r)$ are, respectively, the increments at time $k-i-r$ of the measured output, input and measurable disturbance vectors, where r represents the process time delay. The adaptation mechanism uses the error of the a priori estimation, $Y(k) - \hat{Y}(k|k-1)$, to adjust the AP model parameter matrices $\hat{A}_i$, $\hat{B}_i$ and $\hat{C}_i$ at each time k. On the other hand, following the extended strategy of predictive control, the process output prediction made by (6) can be extended in a prediction horizon. Within this prediction horizon, a performance criterion determines the control vector to be applied to the process.

Also, ADEX COP enables the definition and configuration of the EX and AP domains included in a controller. The controller configuration for AP domains is done systematically [26, 29] by setting the values of the so-called structure variables that determine the operation of the AP control law.

The most relevant of these structure variables are as follows: (i) the *control period* (CP); (ii) the parameters that determine the *AP model structure*, including the process *time delay*; (iii) the *limits on the I/O variables*; (iv) the *noise level* (NL) on the process output; (v) the *rate of change of the desired process output trajectory* (RC), and (vi) the *prediction horizon* (PH).

The ADEX controller configuration for EX domains is done systematically, as explained in [26, 29], by setting the values of tables that determine the rules to be applied for computing the control vector in each specific expert domain.

3.4. Communications architecture

The ADEX COP is connected to the plant through the plant DCS Teleperm XP[¶] as shown in Figure 4. The communications architecture, agreed with Pemex as being the most suitable, comprises the following:

1. Field signals read via OPC.
2. ADEX control signals are directly connected by cable to the DCS with four-20 mA standard.

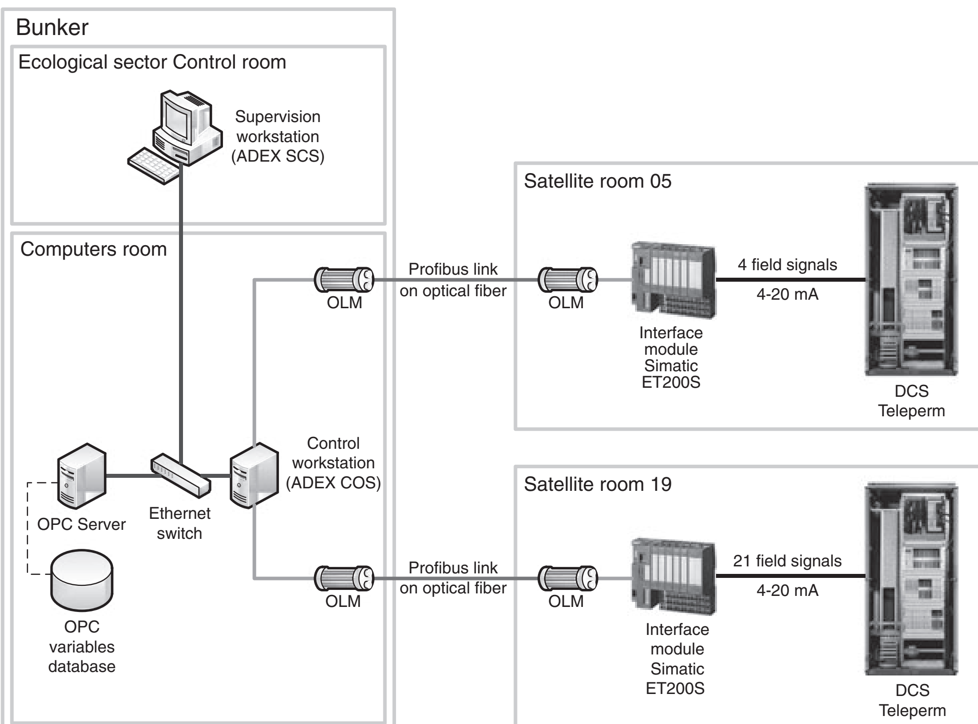

Figure 4. Communication architecture diagram.

[¶]Teleperm XP is a trademark of Siemens.

DOI: 10.1002/acs

The installation of the computer equipment and the communication interface including the physical cabling to comply with the established communications solution was carried out at four locations in the refinery: ecological sector control room, computer room, satellite room 05 and satellite room 19.

The control workstation, where ADEX COS runs, was installed in the computer room and linked to the plant OPC server through an ethernet switch. The supervision workstation, where ADEX SCS runs, was situated in the ecological sector control room and was also linked to the same ethernet network. The ADEX optimized control signals were directly connected by cable to the DCS. A Profibus adapter was installed in the control workstation to link, via Profibus protocol, ADEX COS to the Siemens DCS. A pair of optical link modules (OLMs) was used to connect the computer room via optical cable to satellite rooms 05 and 19 situated near the SRU's. In each of the satellite rooms, the optical signals are converted back to electrical signals, and through the interface modules Simatic ET200S fed to the analog four-20 mA DCS input modules.

4. OPTIMIZED CONTROL STRATEGIES

4.1. *Criteria for optimized control strategies*

The criteria used to define and implement the OCS applied in this project are described in the following points:

- The total amount of acid gas treated by the sulfur recovery plants must be roughly the same, as far as possible in real time, as the total flow of acid gas is being produced by the contributing plants in such a way that the pressure at the common header of acid gas is maintained at equilibrium around a set point.
- The pressure set point at the acid gas header must have a value, which allows the acid gas flow control valve at each of the plants to operate within a desirable range.
- The total amount of acid gas treated by the sulfur recovery plants is distributed in proportion to each of their treatment capacities. This means that the plants in question operate under variable acid gas loads given that the flow of gas from the contributors is, in general, variable. Nevertheless, the plant operators can decide whether any of the sulfur recovery plants are to operate with constant acid gas load if required.
- The criteria expressed in the previous three points must also be applied to the treatment of the ammonia gas produced by the sour-water plants.
- Air flow will be controlled normally by the fine control valve, but the coarse control valve will be used to keep the fine control valve within a desired operating range, ensuring at all times the precise control of air flow at the required set point.
- The set point of air flow will be determined so that the ratio $H_2S : SO_2$ is kept stable and within narrow limits of 2.

The following sections will present (1) the OCS required to maintain the desired pressure in the common header of acid gas, which is practically equivalent to the OCS maintaining the desired pressure in the common header of ammonia gas and (2) the OCS required to maintain the desired $H_2S : SO_2$ ratio by acting on the combustion air two-valve (coarse and fine air) system. These are the main OCS used by the ADEX system to achieve the criteria listed above.

4.2. *Optimized control strategies for pressure in the acid gas common header*

The OCS for pressure in the acid gas common header is shown in Figure 5. Experience shows that pressure in the acid gas lines for the various SRUs is very close and representative of the pressure in the acid gas common header. For this reason, a good estimate of the pressure in the acid gas common header is the maximum pressure in the gas lines. As can be seen on the left side of Figure 5, this maximum value enters as process variable (PV) in the master ADEX controller for the acid gas pressure. This controller receives the measurement of the acid gas flow rates produced by the various plants of the refinery, as perturbations to be taken into account in the predictive model.

DOI: 10.1002/acs

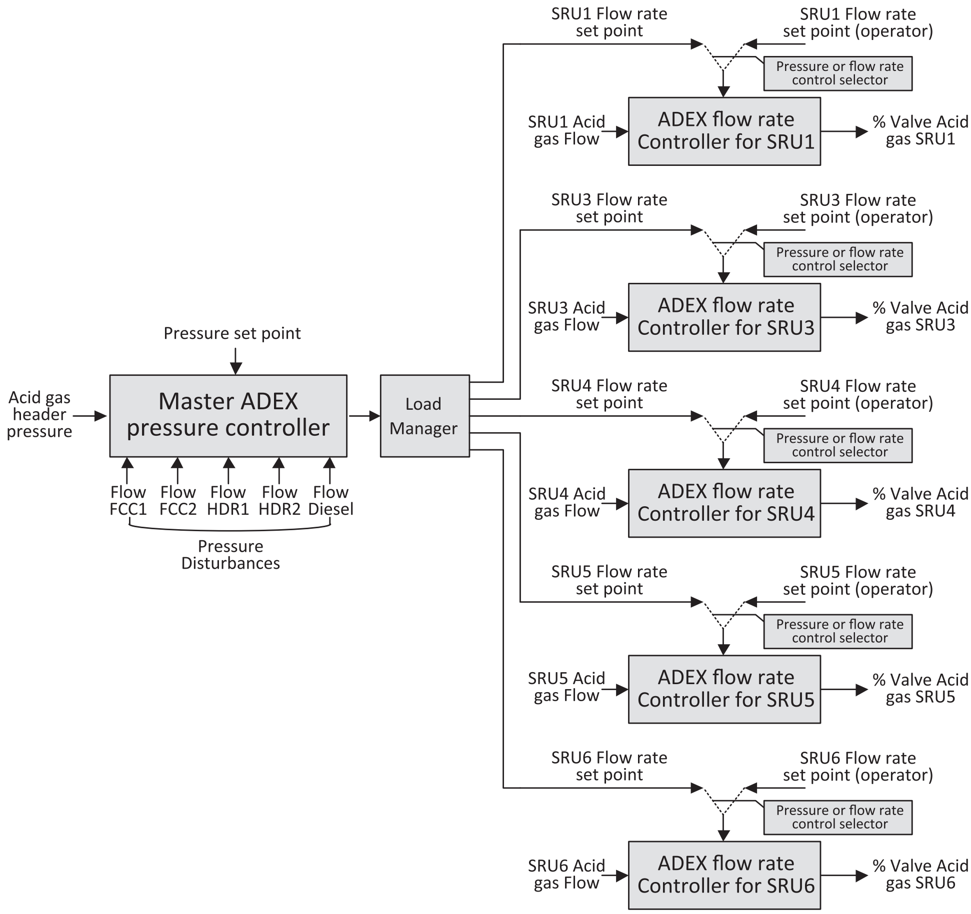

Figure 5. Diagram of the optimized control strategies for pressure in the acid gas common header.

The control signal produced by the master ADEX controller for the acid gas pressure is a master signal, which determines the total acid gas flow rate that needs to be absorbed by the set of all SRUs. This total flow rate of acid gas is distributed by a 'load manager', which sends the set point to the acid gas flow rate ADEX controller of each SRU. The distribution is made to equalize the percentage of acid flow rate treated by each SRU, calculated in relation to the maximum and minimum of the range of variation of these flow rates in each SRU.

On the right hand side of Figure 5, it can be seen how the ADEX flow controllers determine the position of the corresponding flow control valve for each SRU. It can be seen that there is a selector on each ADEX controller, which allows the operator to set a fixed value for the set point as required, thus passing on the action of the corresponding SRU from *pressure control mode* to *flow control mode* of operation. This feature improves the control system flexibility.

This OCS fully satisfies the control objectives since the effects on pressure in the acid gas common header, caused by the variable flow rate of acid gas produced by refinery plants, are anticipated by the AP model of the master ADEX pressure controller and compensated by its control action. This control action, taken through the load manager, makes suitable adjustments to the set points of the ADEX controllers of the acid gas flow rate for the various SRUs.

4.3. *Optimized control strategies for $H_2S : SO_2$ ratio and flow rate of combustion air*

The OCS for the ratio of $H_2S : SO_2$ and the flow rate of combustion is shown in Figure 6. As can be seen on the left side of Figure 6, the ratio of $H_2S : SO_2$ is the process variable for an ADEX

DOI: 10.1002/acs

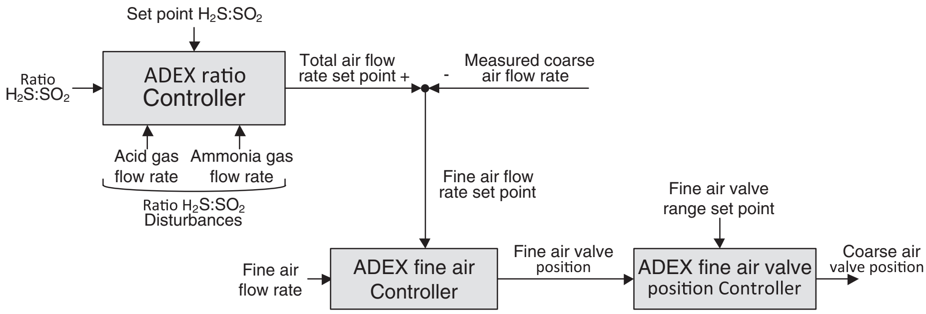

Figure 6. Diagram of the optimized control strategies for the ratio of $H_2S:SO_2$ and flow of combustion air.

controller, which receives as perturbations the flow rates of the acid gas and ammonia gas treated by the SRU, and calculates the set point of the combustion air flow rate as control action.

The strategy for the control of combustion air flow rate includes two ADEX controllers as can be seen in the center and right side of Figure 6. The first one controls the flow of fine air and receives as a set point that of the total flow rate of air minus the flow rate of the coarse air measurement. The second controller receives as process variable, the position of the fine air valve and acts on the position of the coarse air valve so that the fine air valve is positioned within a desired variation range, which is represented as 'Fine air valve range set point' in Figure 6. This indicates that the strategy in this case substitutes the value of the set point for a range of values. Thus, when the position of the fine air valve goes outside this range, the control action will act on the coarse air valve to make it revert back within the range.

In practice, the air demand analyzer (ADA) is used as an equivalent measurement of the $H_2S:SO_2$ ratio. When the ADA is 0, the $H_2S:SO_2$ ratio is equal to 2.

4.4. *Adaptive predictive expert controller configuration*

In order to illustrate the configuration of ADEX controllers, the next part describes the set of values assigned to the structure variables of the ADEX controllers integrated in the OCS for pressure in the acid gas in the common header. In this OCS, there are basically (i) a pressure controller, and (ii) five flow rate controllers.

The pressure controller acts as a master controller with a control period of 2 min. The AP model has a *six input–one output* structure. According to the notation of Equation (5), the process variable $Y(k)$ and the control signal $U(k)$ are scalars, whereas the variable $W(k)$ represents the vector of measurable disturbances for this controller. Although the adaptation mechanism of the ADEX controller is capable of quickly finding and adjusting the AP model parameter values that make the prediction error approach zero, these parameters receive reasonable initial values, on the basis of previous experimentation, with the aim of performing satisfactorily, from the start of controller operations. With reference to Equation (5), the integer values of h, f and g that define the AP model structure are equal to 2, 4 and 3, respectively. So, the parameters $\hat{A}_i$, $\hat{B}_i$ are scalars and $\hat{C}_i$ is a 1×5 vector. Note that with the control period chosen, the process does not show any time delay. The limits on the I/O variables and the noise level on the process output were configured in accordance with the characteristics of the sensors and actuators. The rate of change of the desired output trajectory was chosen equal to $0.13\ \mathrm{kg/cm^2\ per\ CP}$ and the prediction horizon equal to eight control periods.

The OCS for pressure in the acid gas in the common header provides the optimal plant operation combining various control domains within the ADEX pressure controller. Thus, several pressure AP domains were defined using the following criteria: (i) the controller is in *Domain 1*, if only one SRU is used to ensure the control of the pressure in the acid gas common header; (ii) the controller is in *Domain 2*, if two or three SRUs are used to drive the pressure in the acid gas common header, and (iii) the controller is in *Domain 3* if four or five SRUs are in pressure control mode.

The flow rate controller acts as a slave controller with a control period of 6 s. The AP model has a *one input–one output* structure. According to the notation of Equation (5), the process variable

DOI: 10.1002/acs

$Y(k)$ and the control signal $U(k)$ are scalars, whereas the variable $W(k)$ is not present because the main flow rate dynamic is not affected by significant disturbances. As for the pressure controller, a reasonable initial AP model parameter set is defined. The integer values of h, f and g that define the AP model structure are equal to 2, 4 and 0, respectively, so, the parameters $\hat{A}_i$, $\hat{B}_i$ are scalars. With the control period chosen, the process shows only one time delay. The limits on the I/O variables and the noise level on the process output were configured in accordance with the characteristics of the sensors and actuators. The rate of change of the desired output trajectory was chosen equal to $250\ \mathrm{m}^3/\mathrm{h\ per\ CP}$, and the prediction horizon is equal to five control periods.

5. FIELD RESULTS

5.1. Adaptive predictive expert system performance

In Figure 7, the evolution during 24 h of some significant process variables under ADEX control are depicted with the aim of illustrating the operation of the ADEX optimized control strategies. From top to bottom, these variables are as follows: (i) *Graph 1* - the pressure of the acid gas collector and its set point (PV and SP); (ii) *Graph 2* - the total set point for acid gas flow rate; (iii) *Graph 3* - the acid gas flow rate for SRU6 and its set point (PV and SP); (iv) *Graph 4* - the position of the SRU6 acid gas control valve; (v) *Graph 5* - the SRU6 air demand analyzer (ADA) and its set point(PV and SP) and, (vi)*Graph 6* - the SRU6 air flow rate and its set point (PV and SP).

Graph 1 shows the evolution of the acid gas common header pressure (PV) and its set point (SP). Note that the acid gas common header pressure always remains in a narrow band around the header pressure set point. This is possible because of the continuous adjustment of the total acid gas flow entering the sulfur recovery process. This variable is presented in *Graph 2* and represents the control variable produced by the acid gas collector pressure controller.

Note that despite an increase in acid gas load between 12 and 16 h, the pressure remains close to its set point because the OCS for pressure decides at each control period the optimal acid gas flow to be sent to each SRU. This precise control of the pressure facilitates the task of the acid gas flow rate controllers for each SRU.

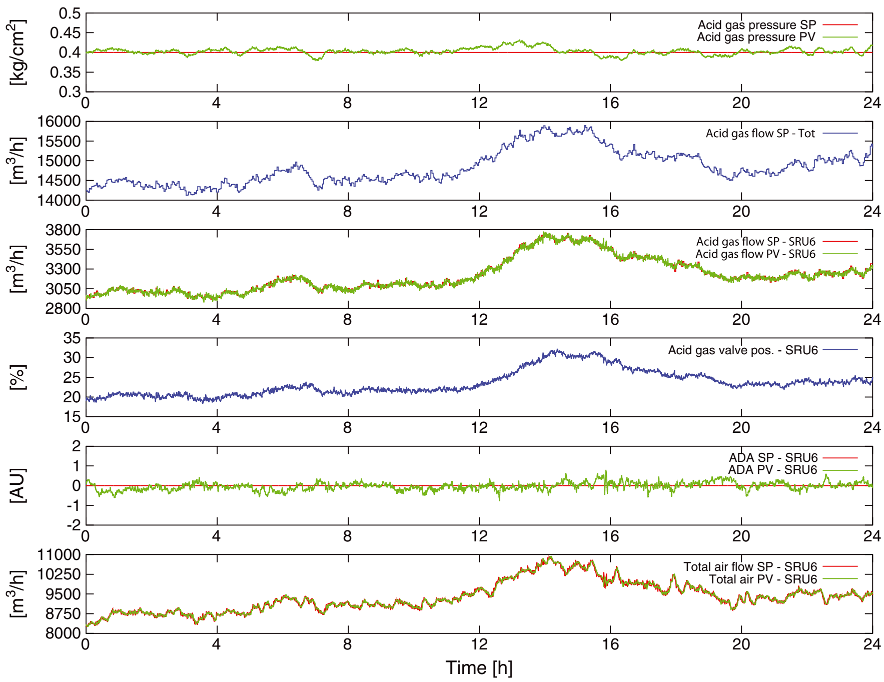

Figure 7. Process operation under adaptive predictive expert control (24 h).

DOI: 10.1002/acs

The collector pressure controller operates as a master controller, as it calculates the total acid gas flow that the set of SRUs should treat. As depicted in Figure 5, a load manager distributes the total load between the different SRUs. In *Graphs 3 and 4* an example of the acid gas flow rate control in SRU6 is shown. The correlation between the total acid gas flow rate treated by the process and SRU6 acid gas flow rate is clearly evident by comparing *Graphs 2 and 3*. The control of acid gas flow rate is so accurate and fast that it is impossible to distinguish the PV from SP in the *Graph 3*.

Graphs 3, 5 and 6 illustrate the performance of the OCS for $H_2S:SO_2$ ratio and flow rate of combustion air in SRU6. As shown in *Graph 5*, the SRU6 ADA remains close to its set point because the $H_2S:SO_2$ ratio controller calculates at each control period the value of air flow rate necessary (*Graph 6*) to keep the $H_2S:SO_2$ ratio stoichiometrically balanced in the presence of variations in the acid gas flow rate (*Graph 3*).

Figure 8 presents 2 h of process evolution included in Figure 7. The following comments can be derived from this more detailed presentation of the same graphs.

- The evolution of the process variable (PV) and the set point (SP) in *Graphs 1, 3, 5 and 6* show the precise control obtained by the ADEX controllers of (a) acid gas pressure; (b) acid gas flow rate for SRU6; (c) analyzer air demand for SRU6, and (d) total air flow rate for SRU6, respectively.
- This satisfactory performance of ADEX controllers is achieved by means of smooth control signals shown in *Graphs 2, 4 and 6* in spite of great variations in acid gas load treated by the set of SRUs.
- It can be observed in the master acid gas flow rate, shown in *Graph 2*, how the control period for the acid gas pressure controller is 2 min, whereas the control period of acid gas flow rate controller in SRU6 is almost ten times faster than that of the master controller.

5.2. *Comparative analysis*

To show the performance improvement achieved by the ADEX system, a comparative analysis with the performance obtained by the conventional control system is presented. Figures 9 and 10 show the evolution of ADA signals when the SRUs are operating under conventional control and ADEX

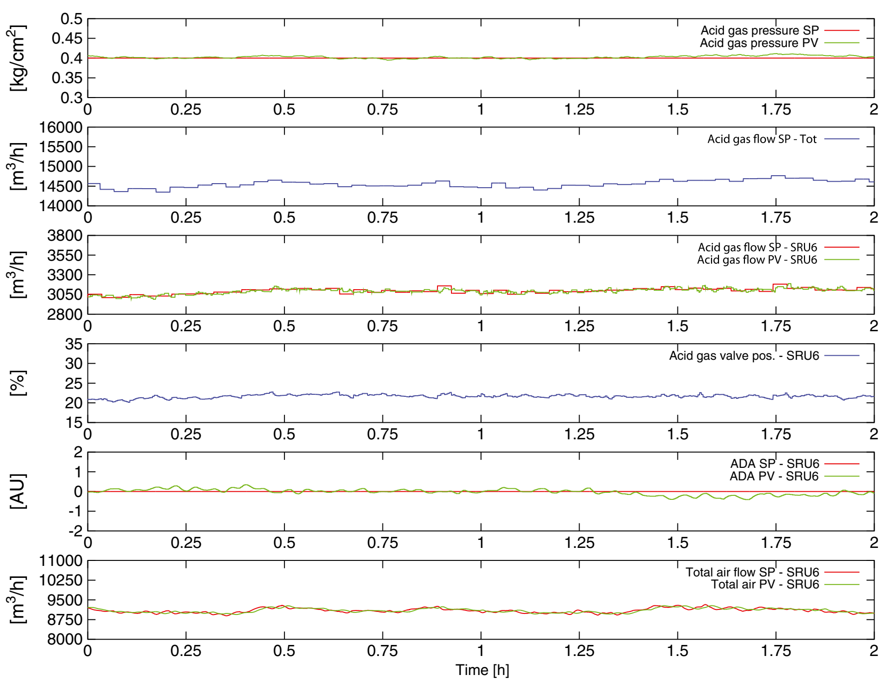

Figure 8. Process operation under adaptive predictive expert control (2 h).

DOI: 10.1002/acs

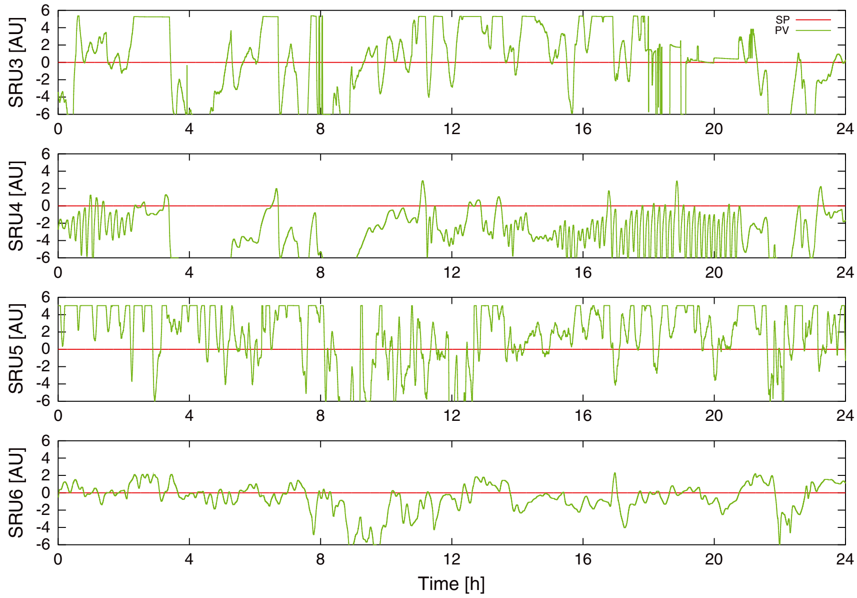

Figure 9. Air demand analyzer signals for the sulfur recovery units 3–6 under conventional control.

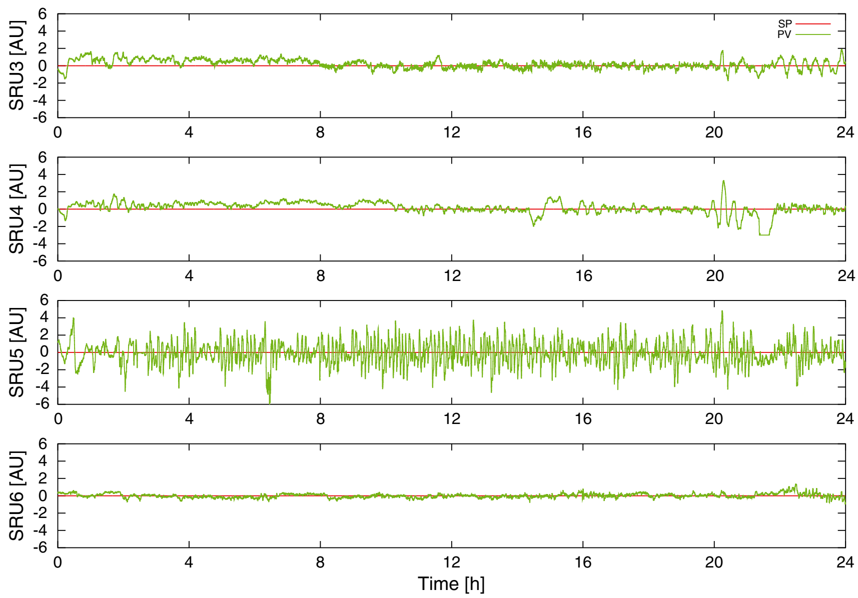

Figure 10. Air demand analyzer signals for the sulfur recovery units 3–6 under adaptive predictive expert optimized control.

control, respectively. The vertical scale of each curve is limited inside a band of ± 6, since the ADA sensor range is limited between $+5$ and -6. The time scale has a span of 24 h. Only the evolution of the ADA signals for SRUs 3, 4, 5 and 6 are shown because SRU 1 was not operating when the data was collected.

When the process is under conventional control, the ADA signals show a large variance, because of an evident control weakness. The measurements of the ADA signal saturate several times for the same reason. In SRU 4, the value of the ADA signal cannot be driven towards its set point. When the process is under ADEX control, ADA signals remain inside a band of ± 1 around the set point.

DOI: 10.1002/acs

Table I. Statistical comparative indices.

Unit name	ADEX control		PID control		St. dev. reduction (%)
	Mean	St. dev.	Mean	St. dev.	
SRU 3	−0.012	0.336	0.797	2.625	87.19
SRU 4	−0.048	0.496	−4.434	1.787	72.22
SRU 5	−0.036	1.386	0.918	3.127	55.68
SRU 6	−0.024	0.196	−0.850	1.308	85.01

ADEX, adaptive predictive expert; St. dev., standard deviation; SRU, sulfur recovery unit.

Only SRU 5 shows larger deviations owing to several instrumentation problems, that is, significant coarse air valve backlash and stickiness.

Table I presents two performance indices for the control of $H_2S:SO_2$ ratio in terms of ADA signal statistics: the average value of the process variable and its standard deviation. These indices are calculated for each SRU under ADEX-optimized control and under PID control. The table also reports the percentage reduction in standard deviation when the process is under ADEX control.

As shown in Table I the minimum reduction percentage obtained by ADEX is 55.68% for SRU 5 and the maximum 87.19% for SRU 3. The average reduction of all units is 65.80%.

6. CONCLUSIONS

In general terms, it has been shown that the application of the strategies designed for ADEX optimized control of the sulfur recovery process has brought about a substantial improvement in the stabilization of the operation of all the SRUs, both as a whole and individually. The most important points in relation to the application of these strategies are presented as follows.

The application of the acid gas pressure control strategy has stabilized this variable and achieved a balanced sharing of the varying load of acid gas entering the various sulfur recovery plants. Thus, a smoother and more controlled variation of the acid gas flows has been obtained for each of the plants capable of absorbing the variable production of acid gas upstream.

The optimized control strategy for the $H_2S:SO_2$ ratio and combustion air has demonstrated its efficiency in spite of the tremendous non-linearity of the operation of the coarse air valves, which are particularly accentuated in SRUs 5 and 6. Indeed, frequently in these plants, the fine air valve appears to have difficulty in coping with the transitions over the full range of variation to compensate for the effects caused by the coarse air valve.

ACKNOWLEDGEMENT

The authors wish to thank PEMEX Refinación and the Cadereyta Refinery staff, engineers and management, for their full support and cooperation during the development of this innovative project.

REFERENCES

1. Smith CA, Corripio AB. *Principles and Practice of Automatic Process Control*. John Wiley and Sons: Hoboken, NJ, USA, 2005.
2. Acedo-Sánchez J. *Instrumentation and Basic Process Control*. Díaz de Santos: Madrid, Spain, 2006. In spanish.
3. Shinskey FG. *Distillation Control for Productivity and Energy Conservation*. McGraw Hill Company: New York City, NY, USA, 1984.
4. Shinskey FG. *Process Control Systems. Application, Design and Tuning*. McGraw Hill Company: New York City, NY, USA, 1996.
5. Martín-Sánchez JM. *Adaptive Predictive Control System*, *US Patent No. 4,197,576*, 1976.
6. Martín-Sánchez JM. *Adaptive Predictive Control System (CIP)*, *European Patent No. 0037579*, 1980.
7. Martín-Sánchez JM. A new solution to adaptive control. In *Proceedings of the IEEE*, Vol. 64. IEEE: New York City, NY, USA, 1976; 1209–1218.
8. Richalet JA, Rault JL, Testud JL, Papon J. Model predictive heuristic control: applications to an industrial process. *Automatica* 1978; **15**:413–428.

9. Cutler CR, Ramaker BL. Dynamic matrix control: a computer control algorithm. *Proceedings of Joint Automatic Control Conference*, San Francisco, CA, USA, 1980.
10. Mehra RJ, Eterno J, Richalet JA, Rault JL. Model algorithmic control: review and recent developments. *Engineering Foundation Conference on Chemical Process Control*, The Cloister, Sea Island, GA, USA, 1982; 287–310.
11. Morari M, García CE, Prett DM, Lee JH. *Model Predictive Control*. Prentice Hall: Upper Saddle River, NJ, USA, 1993.
12. Blevins TL, McMillan GK, Wojsznis WK, Brown MW. *Advanced Control Unleashed: Plant Performance Management for Optimum Benefit*. ISA: Research Triangle Park, NC, USA, 2003.
13. Hovd M, Michaelsen R, Montin T. Model predictive control of a crude oil distillation column. *Computers and Chemicals Engineering* 1997; **21**:893–879.
14. Lautenschlager-Moro LF, Odloak O. Constrained multivariable control of fluid catalytic cracking converters. *Journal of Process Control* 1995; **5**:29–39.
15. Marinoiu V, Paraschiv N, Patrascioiu C, Cartoaje V. Advanced control system for crude oil plant—a case study. *Computers and Chemical Engineering* 1996; **20**:1125–1129.
16. Ansari RM, Tadé MO. Constrained nonlinear multivariable control of a fluid catalytic cracking process. *Journal of Process Control* 2000; **10**:539–555.
17. Porfírioa CR, Almeida-Netoa E, Odloak D. Multi-model predictive control of an industrial C3/C4 splitter. *Control Engineering Practice* 2003; **11**:765–779.
18. Motlaghi S, Jalali F, Nili-Ahmadabadi M. An expert system design for a crude oil distillation column with the neural networks model and the process optimization using genetic algorithm framework. *Expert Systems with Applications* 2008; **35**:1540–1545.
19. Martín-Sánchez JM, Shah SL. Multivariable adaptative predictive control of a binary distillation column. *Automatica* 1984; **20**:607–620.
20. Dumont G, Martín-Sánchez JM, Zervos CC. Comparison of an auto-tuned pid regulator and an adaptive predictive control system on an industrial bleach plant. *Automatica* 1989; **25**:33–40.
21. Cabanillas A, Bahillo A, Cerezo J. Adaptive predictive control in a bubbling fluidized bed boiler. *Proceedings of the 3rd European Conference on Industrial Furnaces and Boilers*, Lisboa, Portugal, 1995.
22. Martín-Sánchez JM, Rodellar J. *Adaptive Predictive Control: From the Concepts to Plant Optimization*. Prentice Hall: Upper Saddle River, NJ, USA, 1996.
23. Pérez L, Pérez J, Cerezo J, Catediano J. Adaptive predictive control in a thermal power station. *International Journal of Adaptive Control and Signal Processing* 1997; **11**:344–367.
24. Huzmezan M, Dumont GA, Gough WA, Kovac S. Adaptive control of delayed integrating systems: a PVC batch reactor. *IEEE Transactions Control Systems Technology* 2003; **11**(3):390–398. DOI: 10.1109/TCST.2003.810385.
25. Martín-Sánchez JM. *Adaptive Predictive Expert Control System. US Patent No. 6,662,058 B1*, 2003.
26. Martín-Sánchez JM, Rodellar J. *Adaptive Predictive Expert Control: Methodology, Design and Application (in Spanish)*. UNED: Madrid, Spain, 2005.
27. Nevado A, Martín L, Sanz J, Alcalde R, Slaven K. Temperature optimization of a naphtha splitter unit. *Advances in Electrical and Computer Engineering* 2008; **8**:7–16.
28. Hiroka K. *Industrial Applications of Fuzzy Technology*. Springer-Verlag: Berlin, Germany, 1993.
29. ADEX SL. Madrid, Spain. 2008. *ADEX Control and Optimization Platform - User Manual*