

Advanced Control System for a Refinery Hydrogen Sulphide Absorption Plant

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The paper presents the research and the results obtained by the authors concerning the advanced adjustment control of the hydrogen sulphide absorption process in the petroleum refinery. This study is structured on four parts. The first part represents an analysis of the actual control system of the absorption process in some refineries. The next two parts contain a detailed presentation of the relation between process model (steady state and dynamic regime) and conventional control systems. In the last part is modeled the advanced control system for the validation and trying of a proposed control system.

Keywords: absorption process, dynamic, hydrogen sulphide, dynamic identification, mathematical modeling, predictive controller

The crude oil processed by some refineries contains 1-2% sulphur and consequently the oil products will naturally contain sulphur- based components. The oil product refining process eliminates the sulphur, but produces hydrogen sulphide, a component that is found in the refinery gases. In order to eliminate the hydrogen sulphide from the refinery gases, is used diethylamine (DEA) as absorbent. The increasing of the absorption plant performances may be also realized by means of the advanced control systems. Problems of the advanced control systems for the absorption process are presented in literature [1-7]. Unfortunately, some refineries work with an old control system. The absence of the advanced control systems from these plants has motivated their researches, materialized through the elaboration of an advanced control system of the hydrogen sulphide absorption process.

The actual control system

Process description

The processing of the refinery gases containing sulphur is based on Gibortol technology. This process realizes the hydrogen sulphide absorption in amine solution. The absorption plant contains an absorption column and a desorption column where the hydrogen sulphide is

eliminated from the amine solution. The absorbent is a diethanolamine solution (DEA).

Hydrogen Sulphide Absorption Plant

The hydrogen sulphide absorption plant is an integral part of a refinery, being known under the name Gas Desulphurization Sulphur Recovery (GDSR). A typical structure of this plant is given in figure 1. The exploitations of the GDSR plant must ensure the fulfillment of the following purposes: a) quality purposes, characterized through the concentration of the hydrogen sulphide from the desulphurized gases; b) financial purposes, given by the exploitation costs; c) environment purposes, expressed through the impact of the combustion of the desulphurized gases.

The feed of the desulphurization plant contains: hydrogen, methane, ethane, propane, butanes, penthenes, carbon monoxide, carbon dioxide and hydrogen sulphide. It is known that the gas feed of a desulphurization plant represents a sum of flows supplied from many plants from refineries, so the flow rate and composition of the feed plant have important variations [8]. Figures 2 and 3 present the typical dynamics for the hydrogen sulphide concentration from feed and for the feed flow rate.

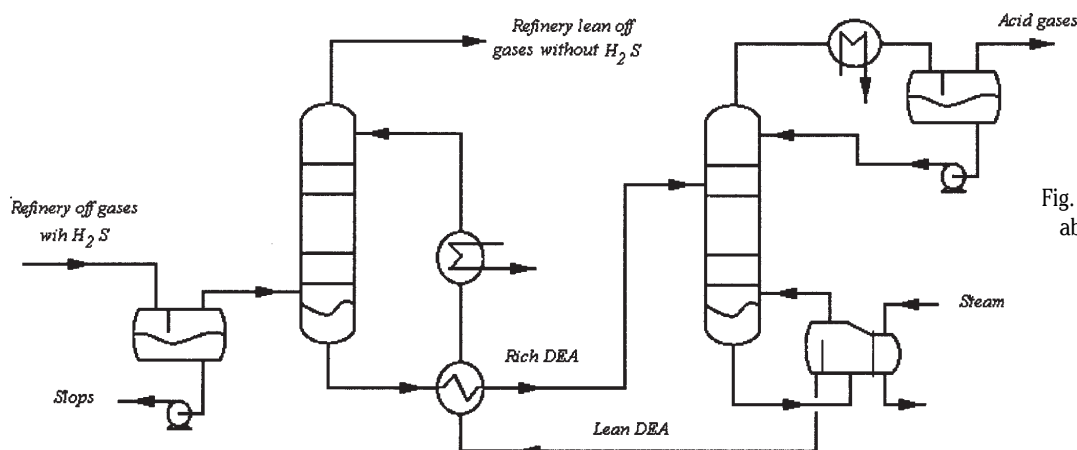


Fig. 1 The typical structure of an absorption unit from a GDSR plant

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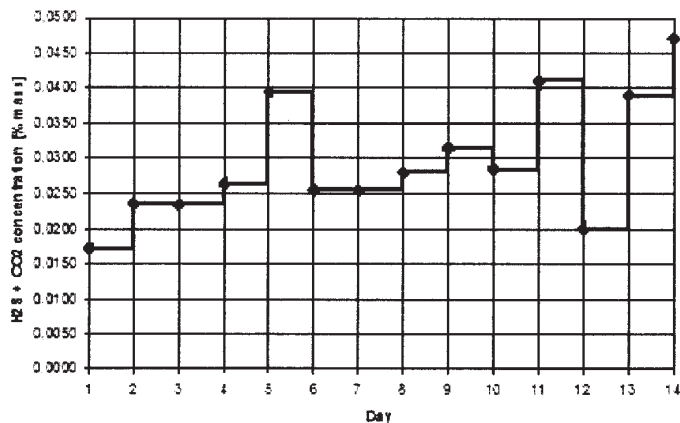


Fig. 2. Dynamics of hydrogen sulphide and carbon dioxide concentration in the feed of DEA absorption plant (Data from Petrotel - Lukoil Refinery; Publication with permission)

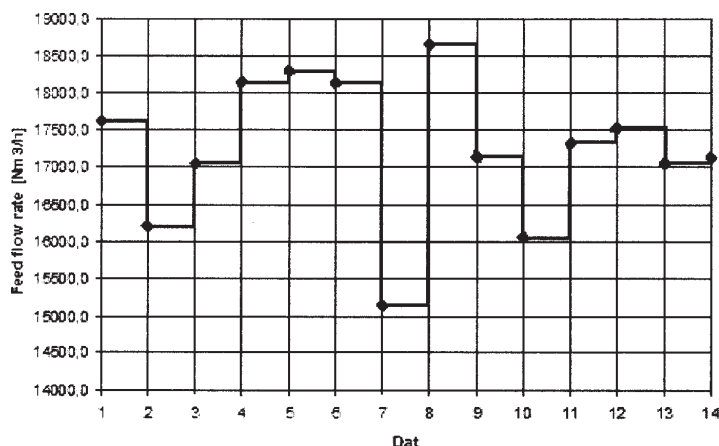


Fig. 3. Dynamics feed flow rate variation of DEA absorption plant (Data from Petrotel - Lukoil Refinery; Publication with permission)

Figures 2 and 3 illustrate the major presence of the disturbances in the feed of the absorption process. It is observed that the cumulated H_2S and CO_2 concentration in the feed flow has a variation of 100% with respect to the low value and the feed flow, and varies with 30% by comparison to the minimum value recorded in the analyzed period. The absorption column feed dynamics, especially the composition dynamics, has a major influence on the process output values, more concretely on the concentration of the hydrogen sulphide in the exit of desulphurized gases, so a control system is needed.

The Actual Control System of the Absorption Plant

The plants from all refineries are equipped with control systems of the most important process parameters. Various structures associated to the H_2S absorption process control

are identified [8]: a) classical control structure; b) control structure based on the control of the ratio absorbent – feed; c) the feedback control structure of the hydrogen sulphide concentration from treated gases.

The investigation (and not only) of the control structure of hydrogen sulphide processing from a refinery, has led to the identification of a general structure, presented in figure 4. Though the absorption column is equipped with a concentration analyzer (hydrogen sulphide) for the treated gases, the actual control structure may be included in the category of the classical structures. The efficiency of this structure is low, mainly because of the effect of the feed composition and flow perturbances. Due to these perturbances, the process output value, the hydrogen sulphide concentration in the treated gases has an important variation; as shown in figure 5. As the admissible superior limit of hydrogen sulphide concentration in the

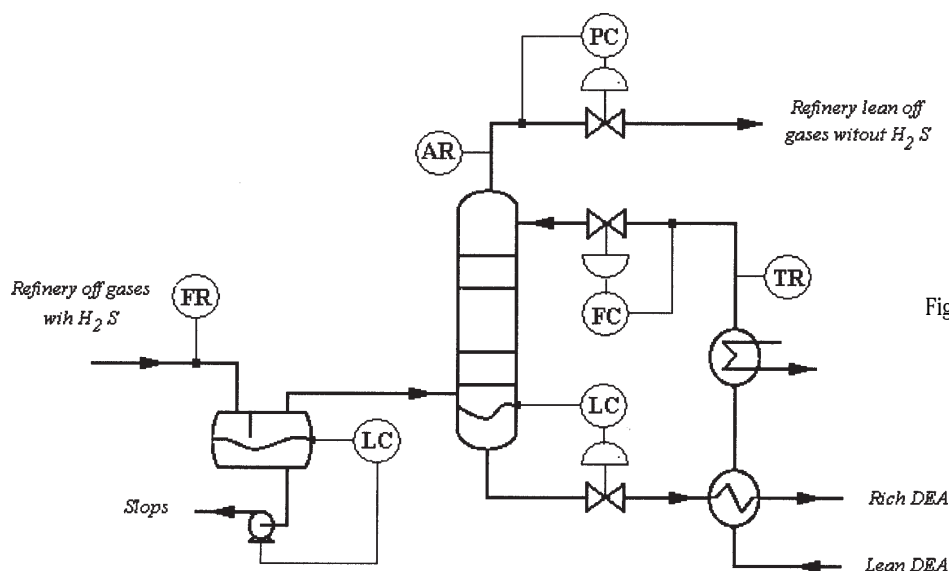


Fig. 4 The process control structure for H_2S absorption column

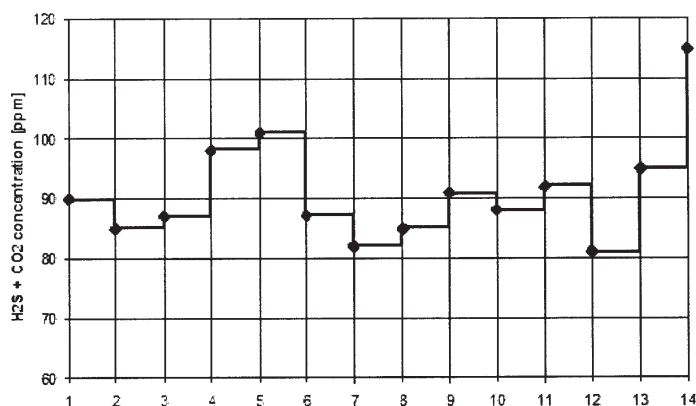


Fig. 5. Performances of the actual control structure (Data from Petrotel - Lukoil Refinery; Publication with permission)

treated gases has been exceeded, the actual control system is considered inadequate.

Design of an advanced control system

For the design of an advanced control system of hydrogen sulphide absorption plant the working stages proposed by means of table 1 have been considered.

The authors' researches have regarded the stages 1-5; the stages 6 and 7 can be realized only with the managing team's permission. The real time programming of the control applications depends on the type of the system distributed by the managers, which is specific to each refinery.

Steady state and dynamic modeling

Steady State Process Modeling

The steady state process modeling represents the first important element within the design stages of the advanced control system. The steady state model is destined to the study of the input-output process characteristics, aiming at the determination of the process sensitivity.

The model of the absorption - desorption process has been decomposed into six subsystems: the absorption column, the fractionation column, two accumulating vessels, a heat exchanger and a detent vessel. The H_2S absorption column is modeled with 8 theoretical plates and desorption column is modeled with 12 theoretical

No.	Step	Objective
1	Process steady state modeling	<ul style="list-style-type: none"> • Generate the steady state process model used in the its modeling • Calculate and analyze the steady state characteristics of the process
2	Dynamic modeling of the process and the basic control systems	<ul style="list-style-type: none"> • Generate the dynamic process model used in the dynamic modeling of the advanced control system • Calculate the dynamic response for each input-output way of the process
3	Dynamic identification	<ul style="list-style-type: none"> • Calculate the transfer function for each input-output way of the process
4	Advance controller design	<ul style="list-style-type: none"> • Controller structure design of the advanced control system • Design the transfer functions of the advance controller
5	Dynamic modeling of the advanced control systems	<ul style="list-style-type: none"> • Generate the dynamic advanced control system model • Tuning the parameters of the advanced controller • Validate the proposed advanced control system
6	Real time programming of the advance controller	<ul style="list-style-type: none"> • Generate the programming code of the real time controller function • Link edit the real time controller function into DCS
7	Operating tests	<ul style="list-style-type: none"> • Real time validate the proposed advanced control system

Table 1
DESIGN STEPS USED TO DEVELOP THE
ADVANCED CONTROL SYSTEM

plates. The two models use the features of the HYSYS program. The specifications of the desorption column (the distillation column) are: the temperature in condenser 90°C; the hydrogen sulphide concentration in the lean diethanolamine at 0.0004 molar fraction.

For absorption process steady state modeling, the authors have tested the simulators HYSYS/UniSim and PRO II [9]. Within the HYSYS/UniSim and PRO II simulator, the authors have selected the thermodynamic model Amine Package completed with the model dedicated for the amine water solution, respectively Li-Mather model [9]. The simulator PRO II has been used with the thermodynamic model Amines Package and the algorithm Chemdist [10]. The analysis of the numerical results obtained by simulation allowed the authors the selection of the simulator HYSYS/UniSim as being the most adequate for determining the steady state process characteristics. The selection has been realized based on the comparison between the experimentally measured concentrations for the hydrogen sulphide in the treated gases. Following the results obtained, the authors have considered that the steady state process model has been validated.

The mathematical model obtained in this way has been used for the study of the absorption process steady state characteristics. Figure 6 presents the dependence between the hydrogen sulphide concentration in the treated gases (the output process variable) and the absorbent flow (the DEA solution).

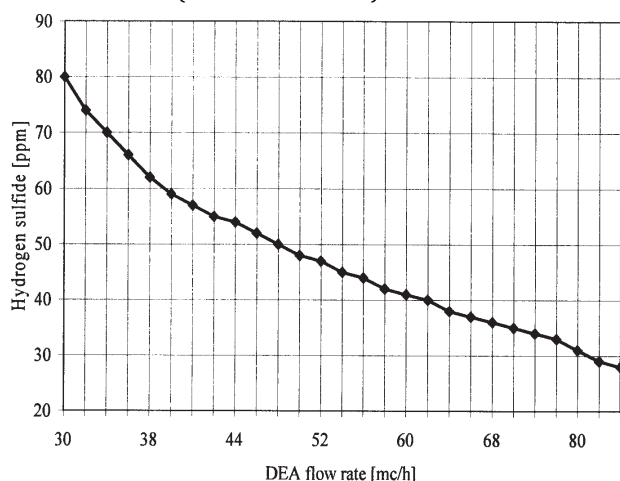


Fig. 6 . Sensitivity of the hydrogen sulphide concentration versus the DEA flow rate

Plant Dynamic Modeling

The absorption plant dynamic modeling represents the second stage of the advanced control system design. The dynamic model has been realized by using the HYSYS simulator, figure 7. The dynamic simulation requires knowledge of the geometrical data associated to the plant, data about the absorption column, distillation column, pumps, accumulation and flash vessels, pipes. The dynamic model of the plant contains the control systems of the pressure and the level, systems based on PID controllers.

An input - output representation of the absorption process is illustrated in figure 8. The input variables are: the DEA absorbent flow (the manipulated variable), the feed flow and the hydrogen sulphide concentration in the feed (the process disturbances). The output variable is the hydrogen sulphide concentration in the treated gases.

In order to study the absorption process dynamics, the input next variables have been modified using the step input:

- The DEA flow rate;
- The feed flow rate;
- The feed hydrogen sulphide concentration.

The effect of the DEA flowrate change is presented in figure 9.

These two diagrams indicate the fact that the significant dynamic elements of the H_2S concentration response (the time constant and the amplifying factor, respectively) are influenced by the steady state value and the step variation of the DEA flow rate. In this respect the authors have identified eight variation domains of the absorbent flow rate: 350-400; 400-450; 450-500; 500-550; 550-600; 600-650; 650-700; 700-750 kmol/h. For each of these domains the dynamic simulation associated to these dynamics has been realized. The dynamic effect of the feed flow change on the H_2S concentration in the treated gas is illustrated in figure 10.

The diagrams indicate the influence of the feed flow value on the dynamic response time and amplitude. In this case, too, the authors have divided the variation domain of the feed flow rate in six sub-domains: 600-650; 650-700; 700-750; 750-800; 800-850; 850-900 kmol/h. For each sub-domain the dynamic simulations have been realized, with were processed afterwards, aiming at the determination of the differential equations associated to the inlet-outlet channel.

Fig. 7. Overview of the HYSYS simulator in dynamic regime

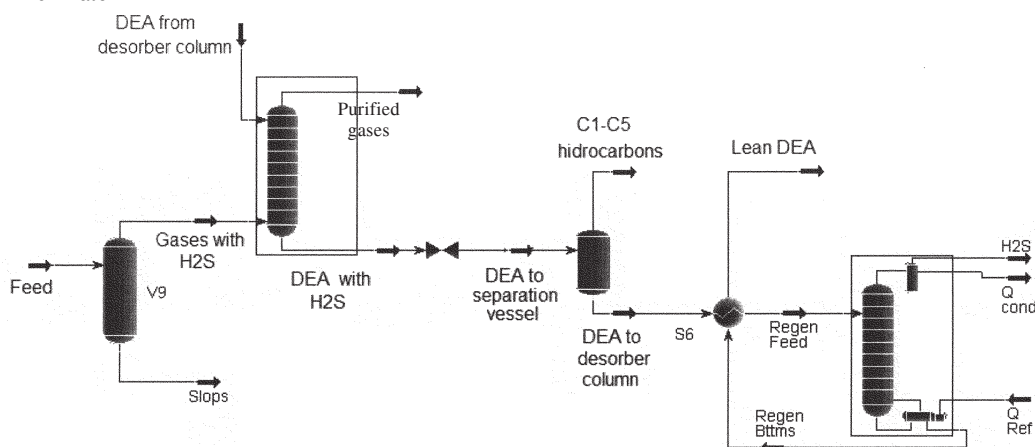
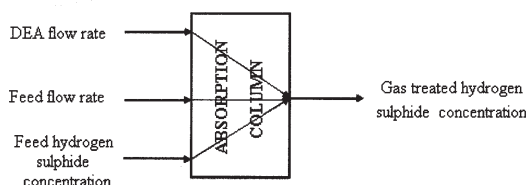


Fig. 8. The input - output absorption process structure



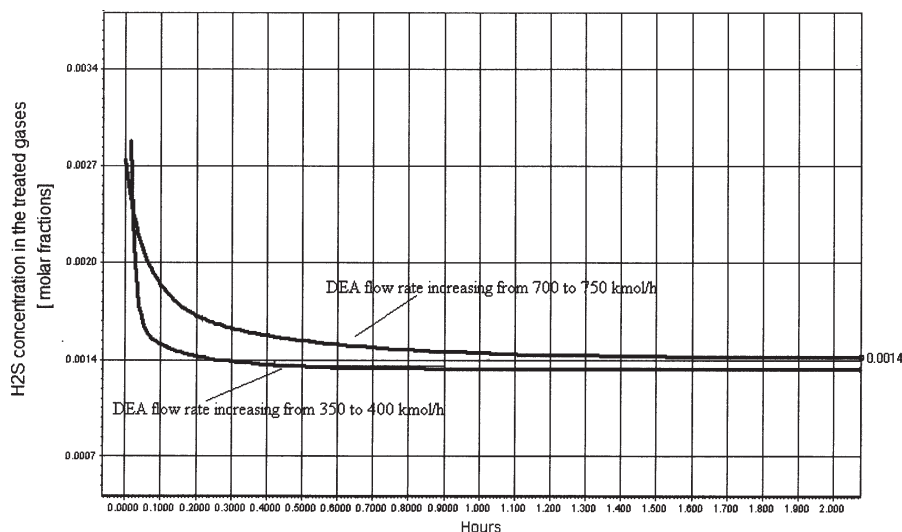


Fig. 9. Dynamics of the H_2S concentration in the treated gas as depending on the DEA flow rate

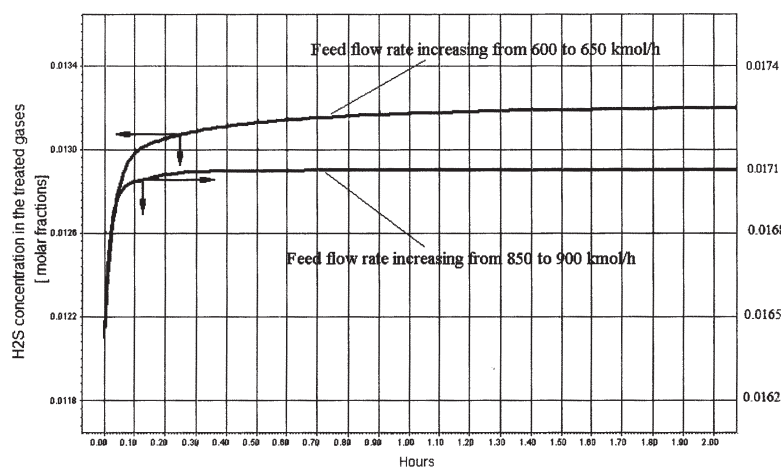


Fig. 10. The dynamics of the H_2S concentration in the treated gas depending on the flow feed

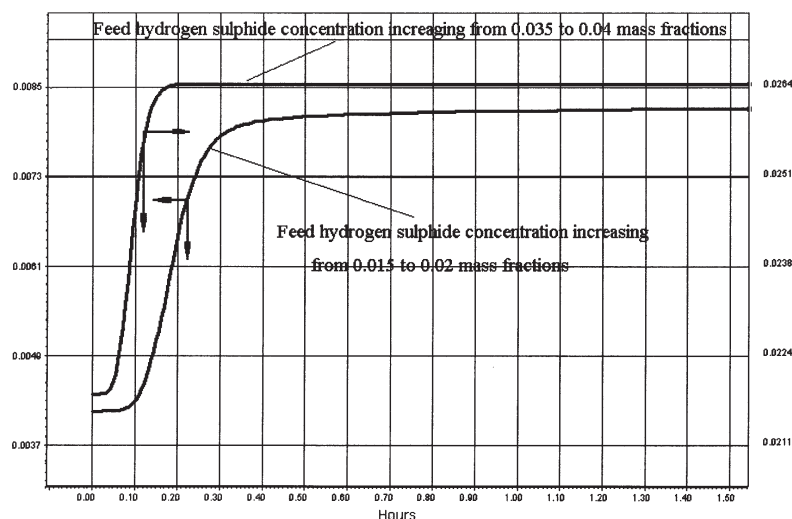


Fig. 11. Dynamics of the H_2S concentration in the treated gas depending on the hydrogen sulphide concentration in the feed

The dynamic simulation produced by the change of hydrogen sulphide concentration from the feed has generated a family of the responses, figure 11. The dynamic response of the H_2S concentration in the treated gas depends on the value of the hydrogen sulphide concentration in the feed. The authors have treated this dynamic response by dividing the variation domain of the feed hydrogen sulphide concentration in six sub-domains presented above: 0.015-0.020; 0.020-0.025; 0.025-0.030; 0.030-0.035; 0.035-0.040 mass fraction.

Dynamic identification

The next state of the advanced control system design consists in the dynamic identification. The dynamic

identification may be realized using graphic methods and numerical algorithms. The graphic methods are as a rough guide when the numerical algorithms have a high precision but are dependent on the inlet data consistency [11-14]. For the identification stage, the authors have proposed many dynamic identification algorithms, algorithms that were largely presented in [15-17]. The analysis of the dynamic simulations presented in chapter IV has emphasized two types of dynamic responses and consequently two dynamic model types: First Order models and Second Order models.

First Dynamic Order Models

The general form of transfer function of the first order model with dead time is

$$G(s) = \frac{ke^{-\tau}}{T_1 s + 1}, \quad (1)$$

where:

k represents the amplification factor;

T_1 - time constant;

τ - dead time.

In order to determine it from a quantitative point of view, the authors have developed three identification algorithms destined to the first order models [16]:

a) The simplified exponential regression.

b) The exponential repression.

c) The multivariable optimization.

The numerical analysis of the three algorithms has proved the fact that the exponential regression is the most adequate identification algorithm for first order models. This algorithm was used for the dynamic identification on the channel flow rate absorbent (DEA) – the H_2S concentration in the treated gas, using the dynamic responses presented in figure 9. Because the dynamic response does not have dead time, the form of the dynamic model is

$$G_{Q_{DEA}-y_{H_2S}}(s) = \frac{k_p}{T_p s + 1}. \quad (2)$$

For each sub-domain of the inlet variable (the absorbent flow rate), the values of the k_p and T_p parameters have been determined, table II. The numerical results obtained by dynamic identification show the fact that both the amplification factor k_p and the time constant T_p depend on the value of the sub-domain of the absorbent flow. This demonstrates the nonlinear character of the process.

The same algorithm, the exponential regression, has been used for the dynamic identification for the channel feed flow rate - the H_2S concentration in the treated gas. Using the dynamic responses of the type presented in figure 10, a first order model without dead time has been proposed

$$G_{Q_{ALIM1}-y_{H_2S}}(s) = \frac{k_{pp1}}{T_{pp1} s + 1}. \quad (3)$$

Table 2

DYNAMIC MODEL OF THE WAY DEA FLOW RATE - TREATED GAS HYDROGEN SULPHIDE CONCENTRATION

DEA flow rate [kmol/h]	k_p	T_p [min]
350 - 400	-0.038	2.5
400 - 450	-0.037	3.5
450 - 500	-0.036	4.4
500 - 550	-0.034	5.3
550 - 600	-0.032	6.0
600 - 650	-0.030	6.8
650 - 700	-0.027	8.0
700 - 750	-0.026	9.4

Table 3

DYNAMIC MODEL OF THE WAY DEA FLOW RATE - TREATED GAS HYDROGEN SULPHIDE CONCENTRATION

DEA feed flow rate [kmol/h]	k_{pp1}	T_{pp1} [min]
600 - 650	0.024	12.6
650 - 700	0.020	9.4
700 - 750	0.017	5.8
750 - 800	0.015	2.2
800 - 850	0.012	1.0
850 - 900	0.010	0.9

Table 3 contains the values of the k_{pp1} and T_{pp1} coefficients for each sub-domain of the feed flow rate.

Similar to the previous case, a non-linear character of the process results because of the dependence of the model parameters on the feed flow rate value. For the channel H_2S concentration in the feed - the H_2S concentration in the treated gas, the analysis of the dynamic response presented in figure 11 has guided the second order dynamic model with dead time

$$G_{y_{ALIM1}-y_{H_2S}}(s) = \frac{k_{pp2} e^{-\tau}}{T_{pp22}^2 s^2 + T_{pp21} s + 1} \quad (4)$$

The value of the time constants T_{pp21} and T_{pp22} have been calculated by using the algorithms elaborated by the authors [17]. The amplification factor k_{pp2} and the dead time τ have been determined by the graphic method. The values of all the model parameters (4), calculated for each sub-domain of variation of the hydrogen sulphide concentration in the feed, are presented in table 4.

Table 4

DYNAMIC MODEL OF THE WAY
FEED HYDROGEN SULPHIDE CONCENTRATION - TREATED GAS
HYDROGEN SULPHIDE CONCENTRATION

Feed hydrogen sulphide concentration [mass fractions]	k_{pp2}	T_{pp22} [min]	T_{pp21} [min]	τ [min]
0.015 - 0.020	0.95	3.7	7.1	4.2
0.020 - 0.025	0.93	3.1	5.9	3.5
0.025 - 0.030	0.92	2.9	5.5	2.0
0.030 - 0.035	0.91	2.7	5.2	1.8
0.035 - 0.040	0.89	2.6	4.9	1.6

The advanced control structure proposal

The structure of the advanced controller

Taking into consideration the influence of the disturbances (the feed flow and the feed H_2S concentration) upon the outlet variable (the H_2S concentration in the treated gas), an advanced control structure has been proposed to maintain the H_2S treated gas concentration set point value and to compensate the

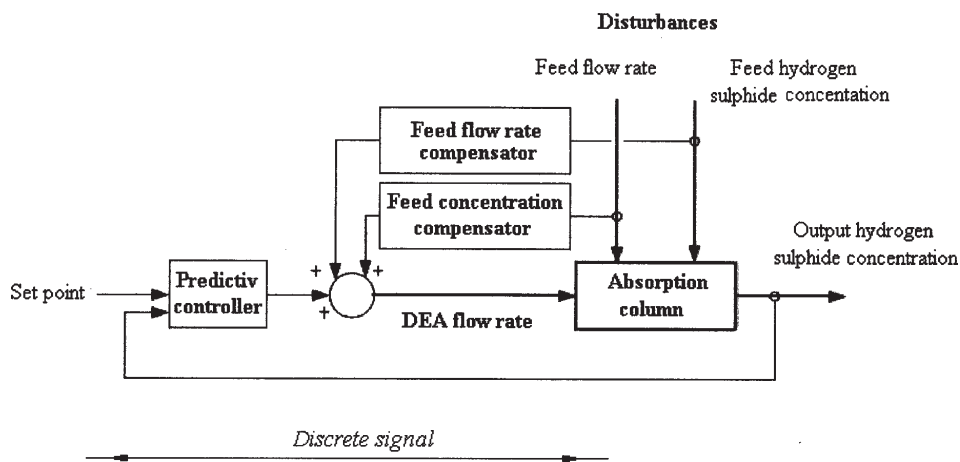


Fig. 12. Advanced control structure

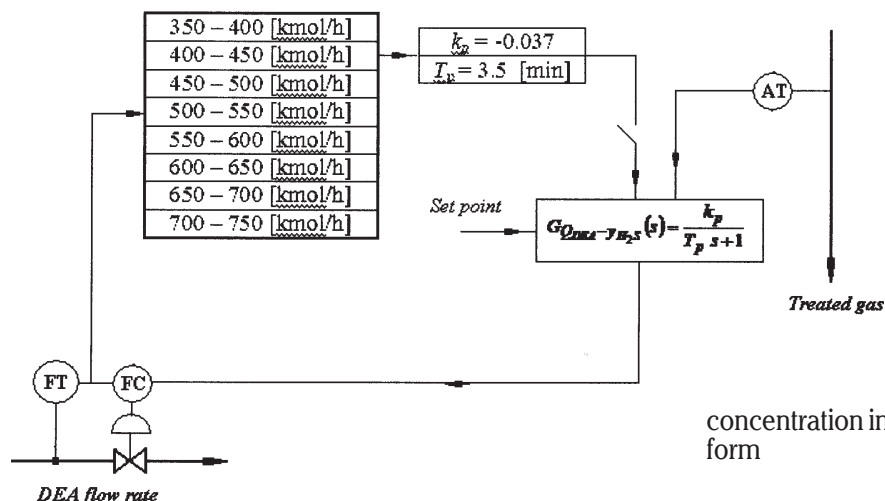


Fig. 13. The domain selector and process model included in structure of the predictive controller

concentration in the treated gas, with the transfer function form

$$G_{MPC}(s) = \frac{k_p}{T_p s + 1}, \quad (5)$$

effects of the two disturbances, figure 12. This control structure combines the feed forward control structure with the strategy of the predictive control [18].

The proposed controller has three components: a predictive controller used for eliminating the errors as compared to the prescribed value and two dynamic compensators that will eliminate the effect of the two disturbances previously enumerated.

The predictive controller structure

The predictive controller includes the process dynamic model on the channel absorbent flow rate (DEA) - the H_2S

where the parameter T_p and k_p keeps the significances presented in relation (2)^p.

Because the process model is divided into eight sub-domains (see table II) and the mathematical model has a non-linear character, the controller will contain a domain selector, figure 13.

The feed flow disturbance compensator

To compensate the effect of the feed flow disturbance upon the H_2S concentration in the treated gas, the introduction of a compensator characterized by the transfer function is proposed

$$G_{CQ_{Feed}}(s) = -\frac{k_{pp1}(T_p s + 1)}{k_p(T_{pp1} s + 1)}, \quad (6)$$

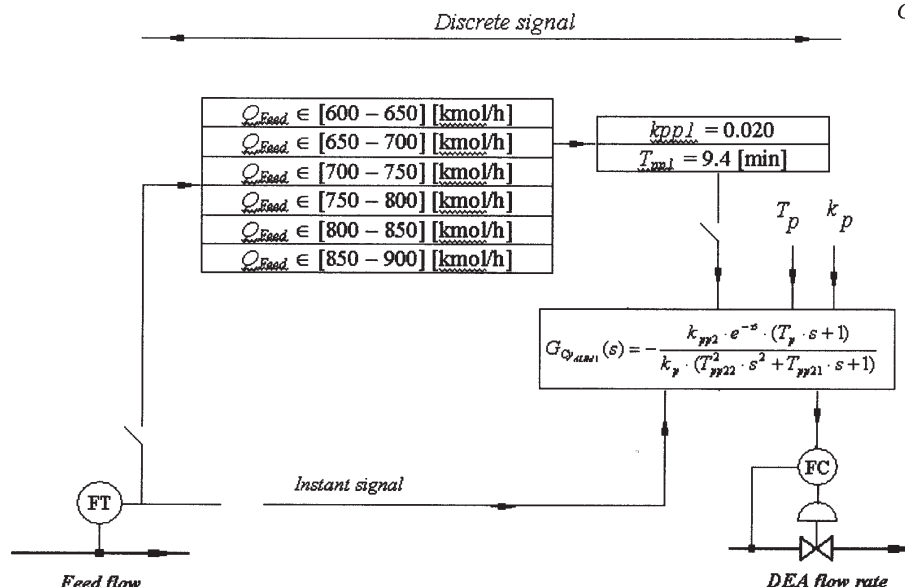


Fig. 14. Structure of the feed flow rate compensator

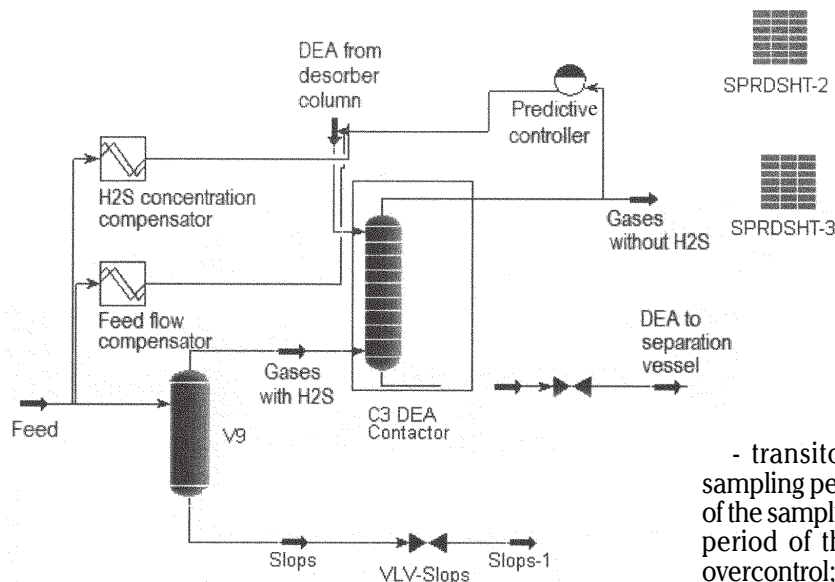


Fig. 15. Dynamic simulator of the advanced control system

where the compensator parameters have the significances presented within section V, the numerical values being detailed in [18]. Similarly with the predictive controller, the structure of the feed flow compensator will include a selector associated to feed flow rate, structure presented in figure 14.

The feed hydrogen sulphide concentration compensator

The compensator associated to H_2S feed concentration disturbance is designed using transfer function associated to this channel of the process

$$G_{CY_{Feed}}(s) = -\frac{k_{pp2} e^{-\tau} (T_p s + 1)}{k_p (T_{pp22}^2 s^2 + T_{pp21} s + 1)}, \quad (7)$$

where the model parameters have the significances presented in the table 5 and the values depend on the variation sub-domain of the hydrogen sulphide concentration in the feed.

The dynamic modeling of the advanced control system

The advanced control system performances have been estimated by the dynamic simulation using the HYSYS® program. In the simulation diagram of the control system the two dynamic compensators and the predictive controller are pointed out, all the models being imported from the simulation environment library, figure 15.

The control system performances have been determined by dynamic simulation at the step modification of both the controller and the two disturbances. Three types of simulation have been realized and are presented below [18]:

- A type simulation, where the control system set point has been modified;
- B type simulation, where the feed flow disturbance has been modified;
- C type simulation, where the disturbance of the feed hydrogen sulfide concentration has been modified.

All simulations have been realized for many sub-domains associated to disturbance values. In the predictive controller have been tested the performances at the sampling period and the horizon prediction changes. The details of the dynamic simulator configuration and the simulation results of the control system are described in [11]. From results analysis of the three dynamic simulation types there have resulted the following conclusions:

- transitory regime periods are dependent on the sampling period of the predictive controller. The decrease of the sampling period leads to the decrease of the response period of the control system, but it can also produce overcontrol;
- controller predictive horizon also influences the transitory regime period;
- both the two dynamic compensators and the predictive controller have good performances, if the mathematical models used by the compensators are in accordance with the sub-domains where the disturbances values vary. In the contrary situation, the control system operation shows a deficit; this will not be able to perform the tasks it has been designed for. This deficiency is due to the process strong nonlinear character and to the linearization operation realized on each sub-domain associated to the disturbances.

Conclusions

The paper contains the most important results of the research carried out by the authors during the period 2006-2012. The purpose of the research has been represented by the study and elaboration of an advanced control system of the H_2S absorption process from the refinery gases, a system that is destined to the Romanian refineries. The study presents the results of the research in the domain of:

- steady state and dynamic modeling and simulation of the H_2S absorption process from refinery gases;
- process dynamic identification to control algorithm elaboration;
- advanced control structure design;
- modeling and dynamic simulation of the advanced control system.

The results obtained have validated the process model (in a steady state and a dynamic state) as well as the advanced control system structure.

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