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Temperature Optimization of a Naphtha Splitter Unit

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***Abstract*—A fully reliable and efficient adaptive control methodology has been long awaited in industry due to the time-varying nature of industrial plants. This paper demonstrates that this kind of adaptive solution is now available and simple to apply by presenting the first application of a methodology called Adaptive Predictive Expert (ADEX) Control in a petrochemical production unit. A description of the plant and the ADEX solution is followed by a comparative analysis of the results obtained with those of the existing conventional PID control. The objectives of the application involving the naphtha splitter at the Puertollano Refinery of Repsol were to establish the viability of ADEX in this environment, increase the quality of the naphtha products by achieving closer compliance with desired specification and maximizing the economic yield. To achieve these objectives it was necessary to enhance the stability of the naphtha splitter by improving control of the principal variables and eliminating a degree of interaction between them which was causing a resonance problem in the column. The application of the ADEX system confirm its viability, demonstrated a marked increase in column stability, significant improvements in levels of control and the elimination of the resonance problems.**

I. INTRODUCTION

Many petrochemical units [1,2] represent a challenge for advanced control methodologies due to their inherent multivariable, interactive, unknown, non-linear and time varying dynamics. The advantages of improving the control performance for this kind of plants are very important and well known; therefore, different control methodologies have been tried in this field, but only a few have proved useful.

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 [3, 4]. However, the simple application of this basic controller can only provide a limited solution to the control problems faced in the operation of many 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 proven of great help in the operation of petrochemical plants [5-7].

The principles of predictive and adaptive predictive control were introduced in the seventies [8-10] and during more than two decades research and publications in this field have 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 [10-13] and are currently being used commercially, mainly in the petrochemical industry.

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.

In the early seventies, a critique of chemical process control techniques [14] used the multivariable control of a binary distillation column as a problem to illustrate the inadequacies of modern control solutions available at that time. Then, the novel technique of adaptive predictive control (APC) was applied in 1975 to this illustrative problem in a pilot unit at the University of Alberta in Canada and the excellent results obtained were first published in a patent application [8] and later in [15]. These results demonstrated that the problems described in [14] already had a new methodological solution. However, although APC has been applied since then in a wide variety of industrial plants [16-20], the subject of this paper is the first adaptive predictive control application in a petrochemical production unit.

Adaptive predictive expert (ADEX) control [21, 23] is the latest generation of APC and enables available plant knowledge to be used within the controller by means of an additional expert block. This new methodology was first applied during a week-trial to several processes at the Repsol-YPF Escombreras refinery [24], and later Repsol-YPF decided to further evaluate ADEX technology for the optimization of the naphtha splitter C-30 at their Puertollano refinery.

To effect a satisfactory separation of heavy and light naphthas, this splitter column requires the control of head pressure, the level of heavy naphtha in the column base, and the temperature of the column. However, the existing PID conventional control resulted in undesirable oscillations in its critical variables, together with frequent resonance between them. Thus, the objectives of the ADEX optimization were to improve the stability and control precision of the column critical variables and the elimination of interactive resonance between them.

A description of the splitter unit and the existing conventional PID control is presented in section II. Section III describes the ADEX methodology, control strategy and implementation. The performance of conventional PID control is presented in Section IV and Section V presents the results obtained by the ADEX implementation. Section V presents a comparative analysis of both implementations and the conclusions are drawn in Section VI.

II. PROCESS DESCRIPTION AND CONVENTIONAL CONTROL

Fig. 1 shows a diagram of the Naphtha 'splitter' column (C-30) with the related units and their connections. It produces light naphthas (LN) from the column head and heavy naphthas (HN) from the base, both of which are final products. The unit is fed by two hydrocarbon streams to the upper part of the column, one of which comes from a stabilizing column (C-25) and the other from an atmospheric distillation column (C-22).

The heating of the splitter column is carried out by a heat exchanger E-30 which transfers the heat to heavy hydrocarbon extracted from the base of the splitter and subsequently recycled to the column. This heat transfer is controlled by means of opening a valve which regulates the heat exchange fluid entering the heat exchanger.

The three main variables which determine the operation of the column are the separation temperature, the level of heavy hydrocarbons in the base of the column and the head pressure at the top. The control system objective is to provide precise control of the separation temperature in order to improve the overall performance of the column. However, it can be seen that there are considerable interactions between the three main variables. Particularly, the effect of variations in pressure on both temperature and level are very significant. As a result, improvement in column performance requires a precise control of all three variables. Under the existing control system, a PID controller was applied to each one of these three main variables.

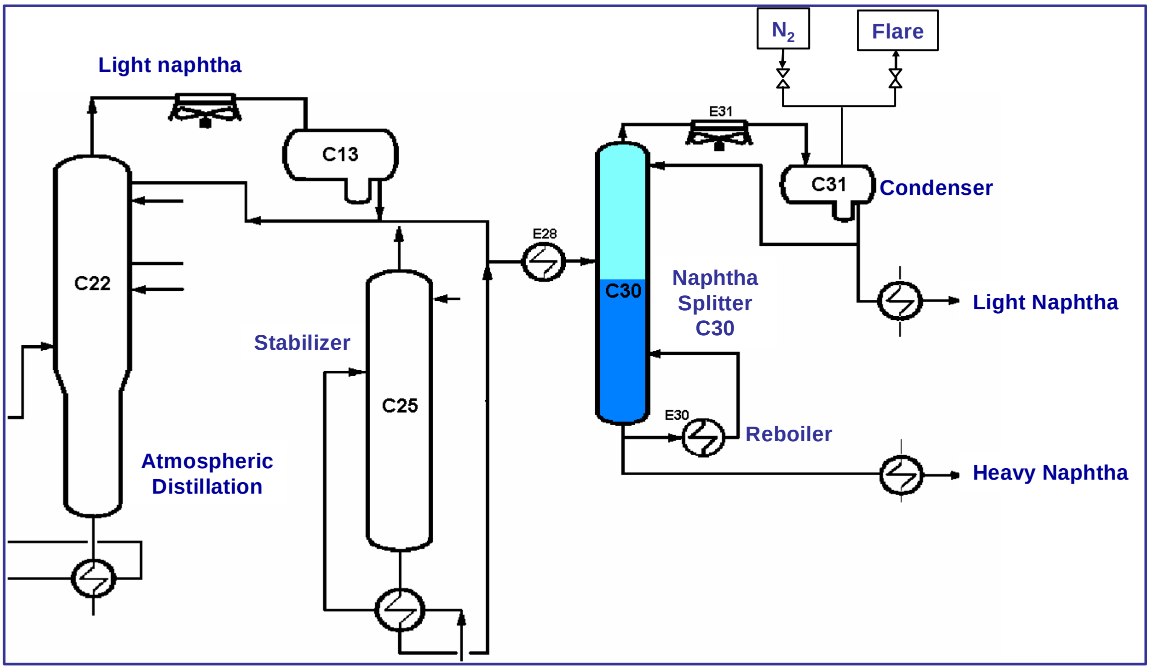


Figure 1. Process Diagram.

The control signal of the PID head pressure controller manipulated two different variables: the opening of the gas exit valve to the flare and the nitrogen injection control valve. The first one is used to compensate for an excess in pressure and the second to respond to a lack of pressure. The instrumentation of the unit was set up in such a way that the head pressure control signal (0 to 100%) had two possible mutually exclusive actions. From 0 to 50% of its range, the control signal varies the opening of the nitrogen injection valve, which is fully open at 0% and fully closed at 50%. From 50 to 100% it varies the opening of the gas outlet valve, which is fully closed at 50% and fully open at 100%. This control signal will be referred as the instrumented head pressure control signal in the following.

Temperature control is achieved by opening or closing the valve which regulates the flow rate of heat exchange fluid entering the heat exchanger, and the heavy hydrocarbon level control in the base of the column is carried out by manipulating the exit flow rate of the hydrocarbon.

III. ADEX METHODOLOGY AND IMPLEMENTATION

III.1 ADEX Domains

ADEX methodology, introduced in the patent application PCT [21], combines APC with expert control in order to offer a complete solution through the definition of operating domains for each of them in an integrated control structure.

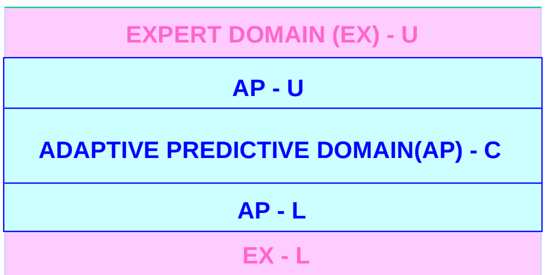


Figure 2. Adaptive Predictive (AP) and Expert (EX) domains.

ADEX methodology enables the definition of adaptive predictive (AP) and expert (EX) operating range limits for process variables under control. Fig. 2 gives an example in which three AP domains have been defined, Central (C), Upper (U) and Lower (L) together with two EX domains, Upper (U) and Lower (L) above and below the AP domains respectively.

The AP domains apply when a cause-effect relationship between process input and output (I/O) variables exists and can be identified by the adaptive mechanism. Within the AP domains, APC is applied to provide optimized control. For each of the AP domains, it is also possible to define and apply a different kind of APC as required.

The expert domains can provide a better solution when, under certain operating conditions, manual control would provide more robustness and efficiency than AP control. This could be the case if the cause-effect relationship between input and output process variables breaks down or cannot be identified in real time, or there is too great a delay in acquiring the necessary measurement or does not, for whatever reason offer a better result than manual control. These operating domains usually exist at the limits of normal operation for the process variables.

Rules derived from operator experience are utilized within expert domains imitating manual control intelligence. ADEX control, within these domains, is designed to drive the process variables towards AP domains and AP control.

III.2 Block Diagram and Functional Description

The general configuration of an ADEX controller [23] is shown in Fig. 3. This section describes the function of each block at each control instant.

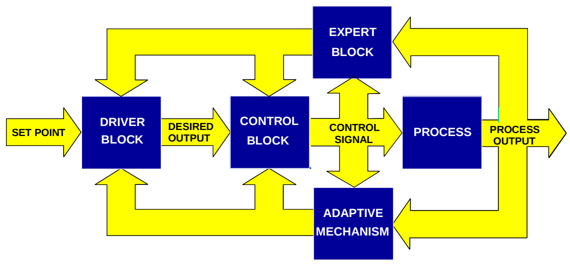


Figure 3. Adaptive Predictive Expert Control Block Diagram.

- The Expert Block determines whether APC or expert control is applicable to the process. In the event that APC is applicable, the Expert block interacts with the other blocks of ADEX as described in the following:

- The Driver block generates a future desired process output trajectory for each process variable. This desired trajectory drives the process output towards the set point, taking into account a desired performance criterion. The expert block can modify the performance criteria according to the ADEX performance required in different domains of the operation.

- The Control Block uses an AP model which defines a mathematical cause-effect relationship between the process input and output variables in order to generate a control vector that makes the predicted process outputs equal to the desired outputs generated by the driver block. When expert control is applied, this block generates the control signal based on rules.

- The Adaptive Mechanism uses the real time process input-output (I/O) measurements to:

  a) Adapt the AP model parameters to minimize the prediction error for each process output variable. However, the expert block determines when adaptation is executed taking into account the operating conditions.

  b) Allow the driver block to redesign the desired output trajectories, taking into account the evolution of the process I/O variables.

In this way, when the process I/O variables evolve in a domain for adaptive predictive control, the expert block will determine the application of APC. The adaptive mechanism will identify the cause-effect relationship of the process, and the control block will be able to predict and control the evolution of the process variables. Thus, as the prediction error becomes close to zero, in spite of changes in the process dynamics, ADEX drives the process output variables along their desired trajectories, and stabilizes them around their set points.

When the process I/O variables evolve in the EX domain, the expert block will determine the application of expert control. In this case, the control block will compute the control vector based on rules imitating human operator intelligence, in a way similar to that of fuzzy logic/expert systems.

The expert block leverages prior knowledge of the process and applies it via rules both in the EX and AP domains. In effect, the expert block provides an overall management function which can determine whether expert control or APC is appropriate or advantageous, and can adapt or re-initialize AP model parameters when required.

III.3 Conceptual Example of Application

In this section, a simple application of ADEX is shown to illustrate the principles. Fig. 4 shows a building climate control example. The heating has been switched off overnight and early in the morning, the system is designed to make the temperature reach 22° C before people come into work. The range of temperatures between 10° C and 22° C is divided into two domains, the AP domain and the Expert domain. Expert control is applicable in a zone where precise control is not required, whereas, precise APC is required closer to the set point of 22° C.

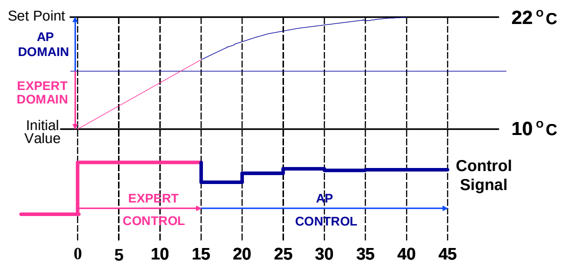


Figure 4. Conceptual example of ADEX application.

At the start, the control signal is zero. Once the control system is in operation, expert control simply does what an operator would do up to about 15 minutes from start up. Thereafter, APC takes over and ensures that the trajectory up to the set point is smooth and avoids oscillations.

III.4 Implementation of ADEX

ADEX technology is applied via the straightforward installation of a Control and Optimization Platform called ADEX COP [22, 23], a Windows based application which can run on any computer linked to the local control SCADA system via OPC or equivalent links.

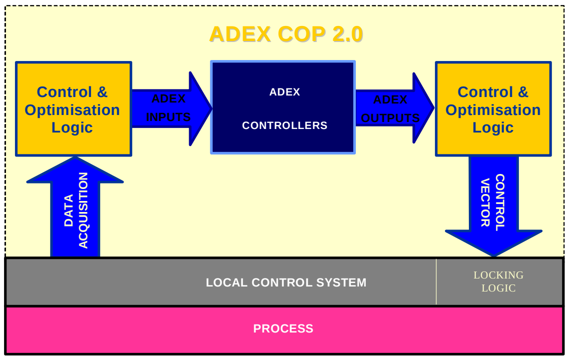


Figure 5. Development and Application of the COS ADEX COP 2.0.

The platform ADEX COP version 2.0 has been developed to enable the design and execution of Control and Optimization Schemes (COS) in which ADEX controllers can be inserted. The platform is designed to operate in parallel to the local control system, virtually without having to modify the local control logic. ADEX COP enables the development and application of the COS using the scheme shown in Fig. 5.

The steps in operating ADEX COP 2.0 are as follows:

- Variables relevant to optimization need to be acquired from the local control system via OPC.

- From these variables COS can be executed to enable the calculation of the optimized control variables to be applied to the process, without having to modify the logic of the local control system.

- Finally, the calculated control variables are sent via OPC to the local control system which will have been prepared to send these control signals to the process. In the event of a communication failure in OPC, a locking logic would revert to the locally generated control signal thereby ensuring total security in the process.

In this way, the COS developed in this platform can be applied independently of the local system and the modification mentioned above (the locking logic) is relatively minor. Apart from the ease of development, the generic nature of the platform also makes maintenance and technical support simpler and cost effective.

IV. PERFORMANCE UNDER CONVENTIONAL CONTROL

Fig. 6 shows three graphs which illustrate the evolution of the three main process variables under conventional PID control during a period of 24 hours. The first graph, Fig. 6a, shows the evolution of pressure and its control signal with the scales of each one on the left hand and right hand respectively. In the same way, the second graph (Fig. 6b) shows the evolution of level with its control signal and the third graph (Fig. 6c) shows the evolution of temperature and corresponding control signal.

In addition, in the right hand column of each graph, there is a frequency histogram (expressed as a % age) summarizing the range of variation of each of the variables from the set point. This histogram reflects the precision of the control applied for each of the variables and displays the position of the mean with respect to the set point and the amplitude of the deviations from the variable.

The time scale is the same for all the variables shown in Fig. 6, which gives visibility to the interactions between them. For example, at 12:00 on 11/05/06 the simultaneous increase in the intensity of the oscillations for all the process variables due to interactive resonance between them can be clearly noticed. This phenomenon occurred frequently during the operation

Table 1 presents a statistical summary of the performance obtained for each of the three main process variables under conventional control over a 24 hour period. This quantifies the mean, standard deviation, variance, maximum/ minimum values and the maximum deviation.

The data in Table 1 demonstrates the following points:

- The pressure has a maximum deviation with respect to the set point of 0.043 bar. The mean converges on the set point and standard deviation is in the order of 7 millibar (+/- 0.0068 bar).

- The level has a maximum deviation of 32.51%. The mean is close to the set point with a standard deviation of 3.79%.

- The temperature has a maximum deviation of 2.87ºC, the peak at the mean being relatively symmetrical, and the standard deviation is 0.68ºC

TABLE 1.

PERFORMANCE UNDER CONVENTIONAL CONTROL

PID Regulation	Pressure	Level	Temperature
Range of measurement	0 - 1 bar	0 - 100 %	0 - 140 ºC
Set Point	0.9	55.0	133.0
Mean	0.899976	54.977456	133.016447
Variance	0.000047	14.422047	0.465088
Standard Deviation	0.006883	3.797637	0.681973
Maximum Value	0.942405	87.512817	135.319901
Minimum Value	0.856463	33.600918	130.128250
Maximum Deviation	0.043537	32.512817	2.8715000

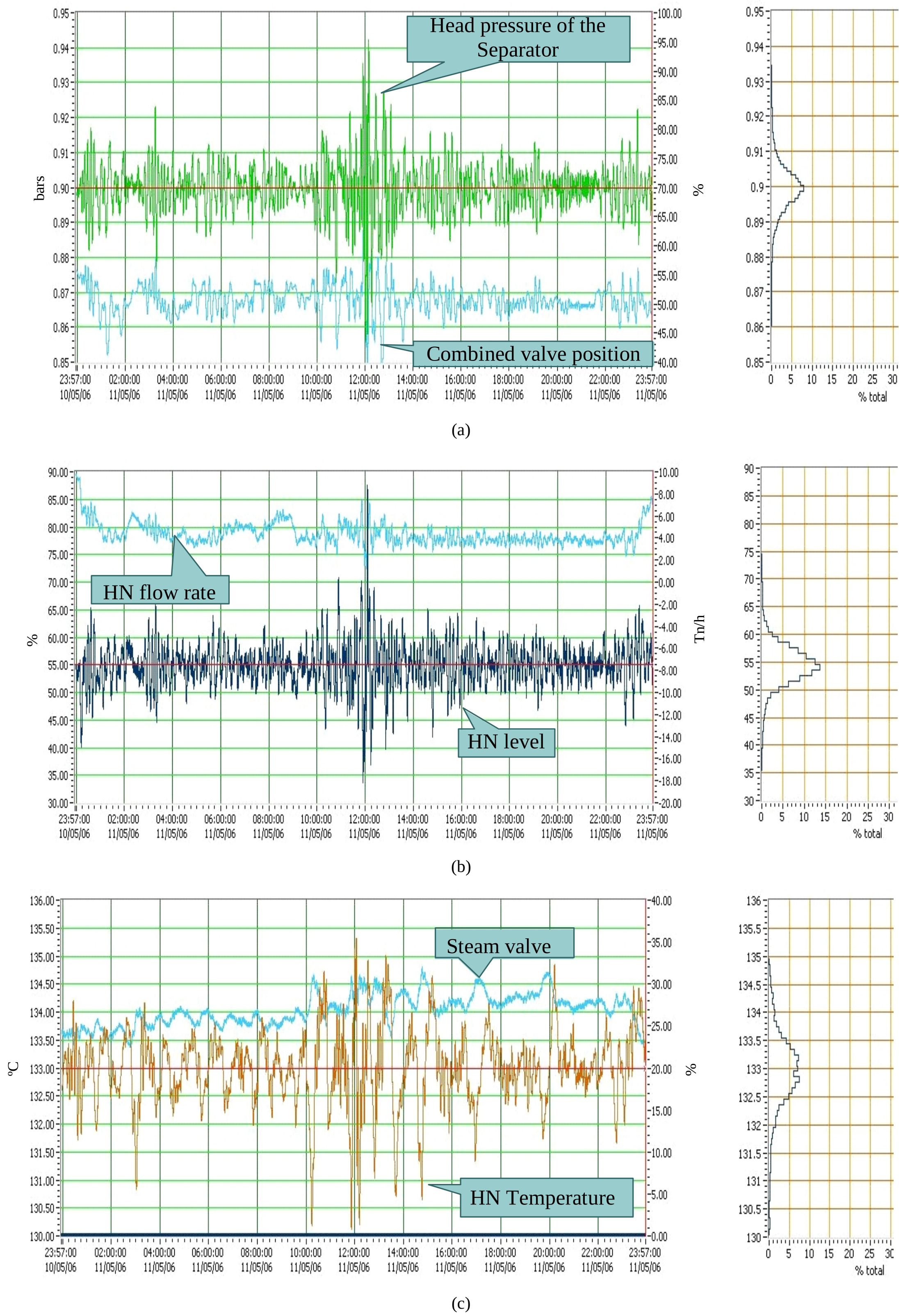


Figure 2 - Control with conventional method: (a) Pressure, (b) Level, and (c) Temperature.

V. PERFORMANCE UNDER ADEX CONTROL

V.1 ADEX COP Implementation

ADEX controllers were applied to the critical variables of the splitter column by means of an ADEX COP platform installed in a PC and connected via Ethernet with an OPC server of the local Honeywell control system.

The demand for data on the OPC server was made every 5 seconds due to operating limitations on the Ethernet network. This sampling period for the updating of data was considered reasonable for the control of the process variables. Using this OPC communication, ADEX control was applied to the three main variables as follows:

a) Pressure Control

The application of ADEX control to the pressure variable involved the operation of two ADEX controllers, one acting on the gas outlet valve and the other on the nitrogen injection valve, both of them using a control period of 2 times the sampling time, that is to say, 10 sec. These two controllers were integrated in a COS for head pressure control developed in the ADEX COP platform in such a way that the control signal range for the ADEX nitrogen injection controller covered 0 to 50% of the instrumented head pressure control signal, and 50 to 100% of this instrumented control signal was covered by the control signal of the ADEX gas outlet controller.

The COS for head pressure control is designed in such a way that both ADEX controllers remain under automatic mode during ADEX control operation, but the instrumented control signal to be applied to the process picks up the value of the control signal from the ADEX controller which is not at 50% of the instrumented control signal scale, unless the control signal of both controllers are at 50%. This means, in general, that when the pressure is under the set point value, and nitrogen injection is needed, the nitrogen injection controller will produce a control signal corresponding to a value lower than 50% of the instrumented control signal scale, while the ADEX gas outlet controller output will correspond to the 50% scale of the instrumented control signal, i.e. the gas outlet valve will be closed. The instrumented control signal will then pick up the output value of the ADEX nitrogen injection controller and nitrogen will be injected. When the pressure is over the set point value, a converse operation of the ADEX strategy will apply. In this way, both ADEX controllers complement each other in operation and the process always receives the appropriate control action according to the evolution of the head pressure.

Both ADEX controllers consider each other's control signals as measurable perturbations, i.e. variables that are inputs in their respective predictive models. In this way, the interaction between the operations of both controllers is taken into account particularly when the control signal applied to the process switches from one to the other.

b) Level Control

The level control of the heavy hydrocarbon in the base of the column is carried out by means of an ADEX controller which manipulates the flow rate of the heavy hydrocarbon at the outlet from the column. This controller considered the inlet feed flow rates to the column as perturbations. The control period is 30 seconds.

c) Temperature Control

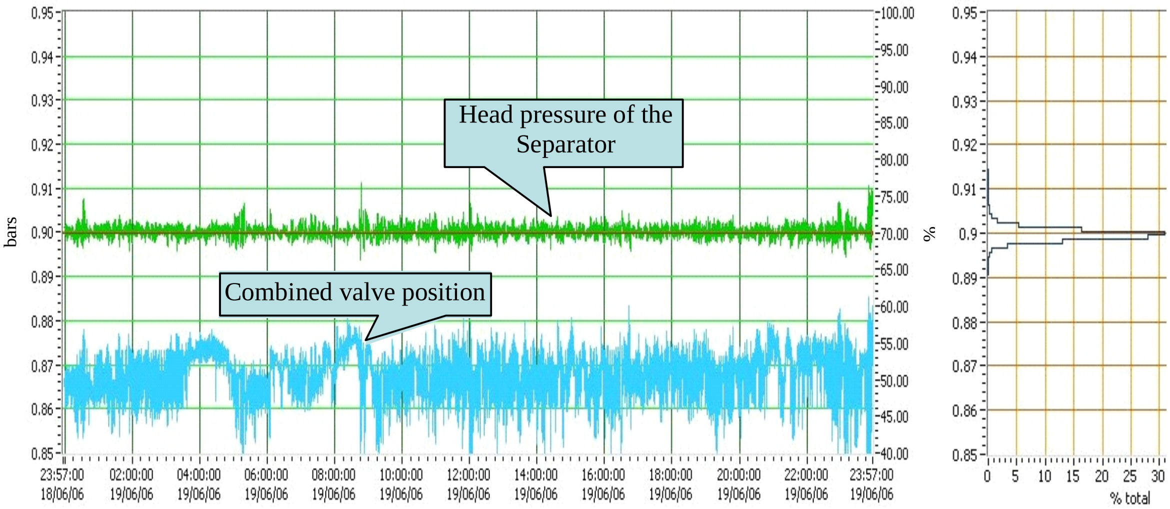
The separation temperature control in the column is achieved by means of an ADEX controller which acts on the opening of the valve regulating the flow rate of the fluid entering the column heat exchanger. This controller considers the light and heavy naphtha feed temperatures and the pressure in the column head as perturbations. In this case, the control period is 60 seconds.

V.2 ADEX Control Performance

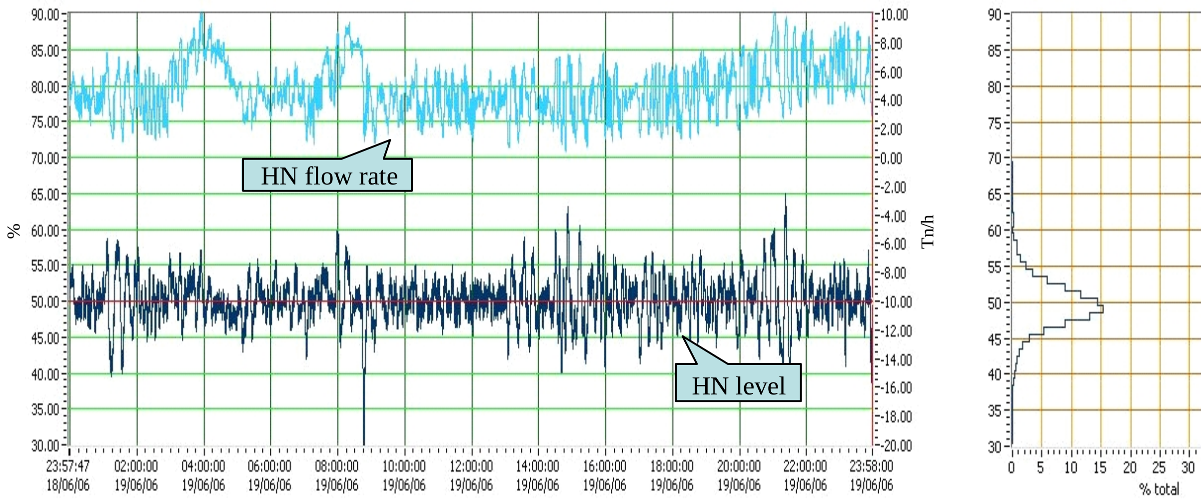
The evolution of the process variables under ADEX control during a period of 24 hours is shown in Fig. 7. As in the case of conventional PID control in Section III, a graph is presented showing each of the process variables controlled by ADEX. They are presented in order of pressure (Fig. 7a), level (Fig. 7b) and temperature (Fig.7c) along with their respective control signals and corresponding frequency histogram.

The variables are shown with the same units and scales as shown in Fig. 6 to facilitate comparison. The frequency histograms are shown with the same scales, representing the frequencies of process variables as a percentage over the total and with a similar sample size in each case.

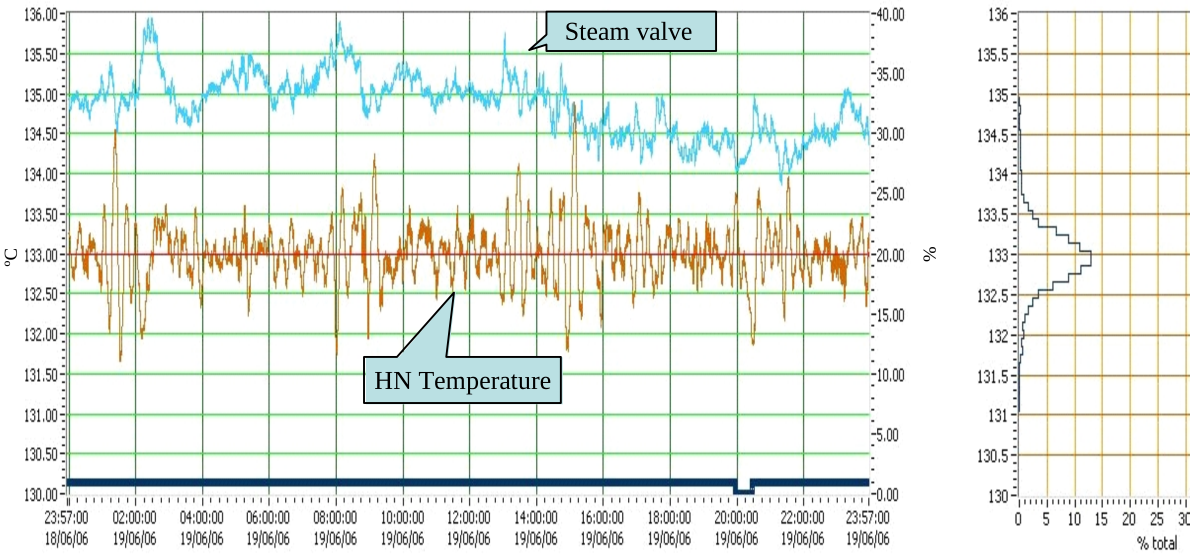
Table 2 shows the statistical results of ADEX control performance over a period of 24 hours, similar to Table 1 which showed equivalent statistics for conventional PID control.



(a)



(b)



(c)

Figure 3. Control under ADEX: (a) Pressure, (b) Level, and (c) Temperature.

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TABLE 2

STATISTICS OF THE PROCESS CURVES UNDER ADEX CONTROL

ADEX CONTROL	Pressure	Level	Temperature
Set Point	0.900000	50.000000	133.0000
Mean	0.900197	50.028710	132.998559
Variance	0.000002	10.394441	0.145025
Standard Deviation	0.001446	3.224041	0.380821
Maximum Value	0.911395	64.882935	134.896301
Minimum Value	0.880593	24.486973	131.654877
Maximum Deviation	0.019407	25.513027	1.896301

The following points are highlighted from the Table 2

- The pressure has a maximum deviation with respect to the set point of 0.019 bars. The typical deviation is +/- 1.5 millibar.
- The level has a maximum deviation of 25.51%. The typical deviation is +/- 3.22%
- The temperature has a maximum deviation of 1.89 ºC and the typical deviation is +/- 0.38ºC.

In addition, the phenomenon of interference or interactive resonance between the variables in the column found during conventional PID control was eliminated under ADEX control.

VI. COMPARATIVE ANALYSIS

Figs. 8, 9, and 10 present histograms for pressure, level and temperature obtained during a period of 24 hours under conventional PID control and ADEX control for the purposes of comparison.

Table 3 presents a summary of the statistical analysis of performance under both types of control , where standard and maximum deviations for all three process variables are compared.

A. Pressure control

The pressure control was improved markedly by ADEX control, reducing maximum deviations by half over conventional PID control and reducing the standard deviation by a factor of 4.7. The variable does not undergo excursions so far from the set point, and the band of oscillations is considerably reduced.

It was proved experimentally that the intensity of pressure oscillations significantly affected the level and temperature variables. When ADEX was applied to pressure control, the effect of the large pressure oscillations on the level and temperature control was also reduced as a consequence and this in turn avoided the resonance phenomena between the variables.

In Fig. 8, the histograms of both control methods are shown. It can be seen how they are centered around the set point, and how the profiles of the graphs in the case of ADEX control are much more peaked around the set point, with smaller tails at the ends. This demonstrates more precise control with fewer excursions away from the set point.

B. Level Control

Once the pressure was stabilized by applying ADEX, the level control also achieved a reduction in maximum deviations, this time by 20% and a reduction in standard deviation by 15%. The variable oscillated 66% of the time between +/- 3.2 %. In addition to improving the level control, the set point of the level was reduced to 50% from 55% which was the previous normal level.

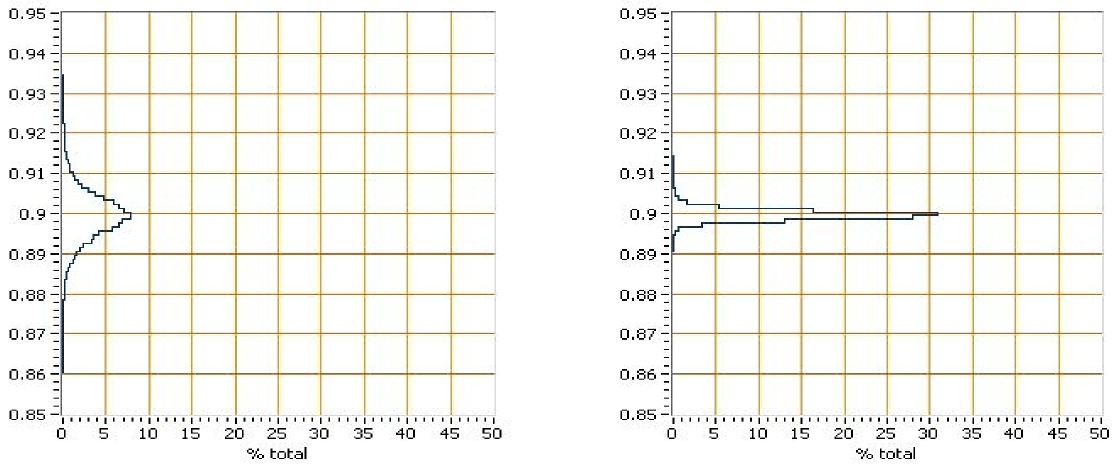
C. Temperature Control

The control of temperature improved by reducing the maximum deviation by 37% from 5.2ºC to 3.2ºC and a reduction in standard deviation to almost half i.e.+/- 0.68ºC to +/-0.38ºC.

TABLE 3

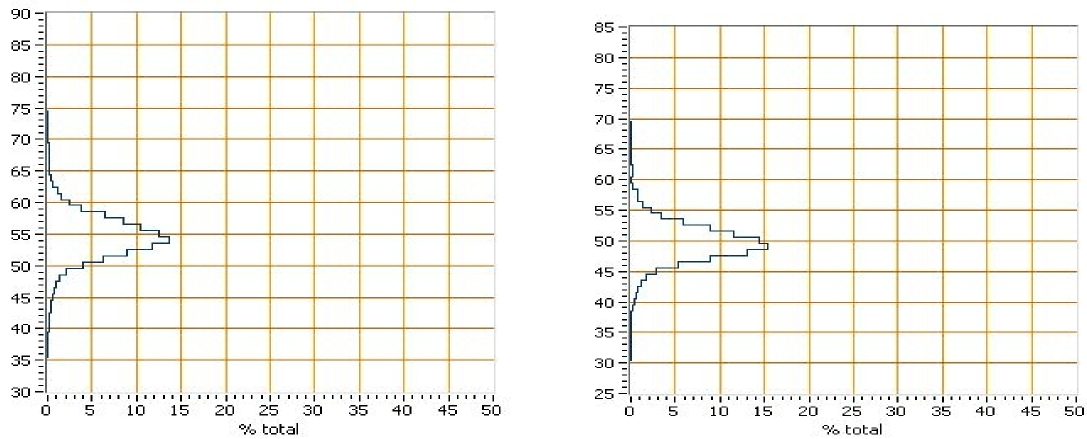
COMPARISON OF PERFORMANCE UNDER BOTH CONTROL METHODS

Variable	Pressure		Level		Temperature	
Control method	PID	ADEX	PID	ADEX	PID	ADEX
Standard Deviation	0.006883	0.001446	3.797637	3.224041	0.681973	0.380821
Maximum Deviation	0.043537	0.019407	32.512817	25.513027	2.8715000	1.896301



PID Control **ADEX Control**

Fig.ure 8. Frequency Histogram of pressure control under PID (left) and ADEX (right) control. Frequencies expressed as % of total number of values.



PID Control **ADEX Control**

Fig.ure 9. Frequency Histogram of level control under PID (left) and ADEX (right) control. Frequencies expressed as % of total number of values.

PID Control **ADEX Control**

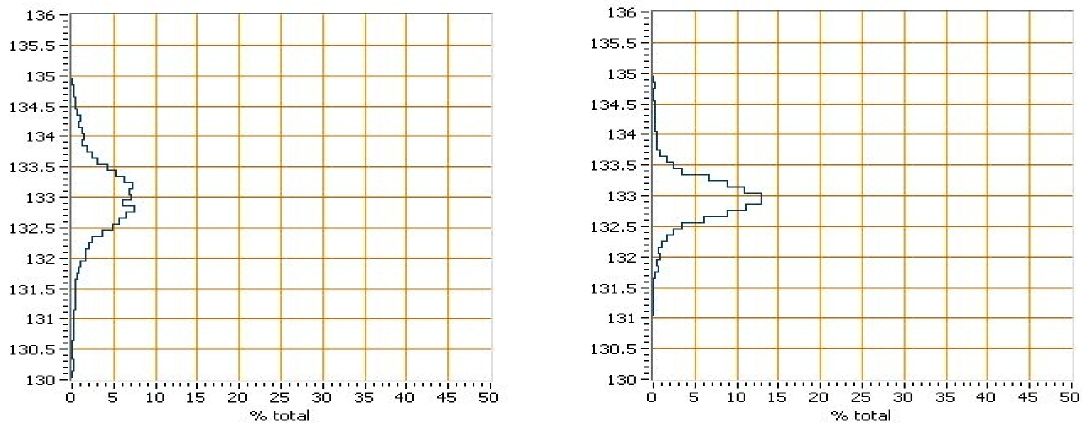


Fig.ure 10. Frequency Histogram of temperature control under PID (left) and ADEX (right) control. Frequencies expressed as % of total number of values.

VII. CONCLUSIONS

The ADEX implementation presented in this paper was shown to be a fully reliable and efficient adaptive control solution in the context of a live petrochemical plant operation. The use of the software platform ADEX COP made the application extremely simple and allowed the application of ADEX control in parallel to the local control system, virtually without having to modify the local control logic.

The following improvements of ADEX implementation over the existing conventional one were demonstrated:

- A greater precision in the control of the three critical variables of the naphtha splitter column , particularly the column head pressure and the splitter temperature.
- Greater stability overall in the operation of the column
- The disappearance of the frequent resonance phenomena which characterized the operation under conventional control.

The success of this first application has shown that an adaptive control technique such as ADEX can now be used instead of conventional PID controllers in a systematic and simple way, providing enhance stability and precise control, thereby optimizing plant performance.

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