MODEL REFERENCE ADAPTIVE CONTROL OF AN INDUSTRIAL PHOSPHATE DRYING FURNACE

B. Dahhou, K. Nijim, M. M'Saad and B. Youlal

Laboratoire d'Electronique et d'Etude des Systèmes Automatiques, Faculté des Sciences, B.P. 1014, Rabat, Morocco

Abstract. This paper presents experimental results of a model reference adaptive control algorithm with independent tracking and regulation objectives presented in (Landau, Lozano, 1981) to the control of a phosphate drying process at the Beni-Idir Factory of the OCP (Office Cherifien des Phosphates - Maroc).
The main control objective is to keep the moisture content of dried phosphate at a prescribed value (1,5 %), independently of external perturbations acting on the drying process.
The plant dynamic characteristics vary under the effect of variations of the input material characteristics such as the phosphate nature and humidity that vary from one layer to another.
The implementation of the adaptive algorithm was based on a reduced order plant model previously checked and uses a small size minicomputer.
An energy saving close to 4,5 % and ten times reduction of the variance of the output humidity error with respect to the desired one were obtained. This led to the motivation of introducing an advanced computer control in Moroccan Phosphate Industry.

Keywords. Adaptive Control ; Model Reference ; Energy Saving ; Phosphate Processing ; Drying Furnace.

INTRODUCTION

During the past few years different approaches to adaptive control have been suggested, studied and applied. Among these approaches, the Model Reference Adaptive System and the Self-tuning Regulator seem to be the most attractive ones.

This paper deals with the application of a Model Reference Adaptive Control Algorithm, presented in (Landau, Lozano, 1981), to the control of a Phosphate Drying Process at the Beni-Idir Factory of OCP.

The phosphate, independently of its way of extraction has about 17% humidity. Before being sold, this high humidity has to be reduced to around 1,5% in Rotary Drying Furnaces.

The drying process is one of industrial operations that requires a great consumption of energy, hence an increase in the price of the produced dried material.

The objective of this study is to keep the humidity of the dried phosphate close to the prescribed value (1,5%), independently of raw material humidity variations (7 $\sim$ 20%) ; feed flow rate variations (100 $\sim$ 240 t/h) and other perturbations that may affect the drying process.
There is, invariably, some uncertainty in the characteristics of the processed phosphate that can be attributed to variable moisture content and the nature of the damp product.

The phosphate drying process is therefore non-linear and non-stationnary in its nature. The change in dynamic characteristics with operating conditions is such that a fixed parameter controller is inedequate to achieve satisfactory performances in the entire range over which the characteristics of the process may vary. An adaptive control holds obvious attractiveness in such situation because controller parameters are adjusted during operation to maintain specified dynamic performances.

A Model Reference Adaptive Control Scheme, developed by I.D. Landau and R. Lozano and based on reduced order plant model, previously checked was implemented using smale size minicomputer.

The main motivations of such control scheme are the following :

- It is simple : i.e. it can be implemented even on microcomputer.
- It ensures the asymptotic convergence of the plant output (the humidity of the dried phosphate) to the reference sequence and the boundness of the control applied to the plant.
- It allows to solve the problem of

independent specification of tracking and regulation objectives.

This paper is organized as follows. In section II, we provide physical description of the used drying process. In section III, a mathematical model of the drying furnace is formulated. In section IV, the adaptive control scheme used to control the phosphate drying furnace is presented while in section V, the hardware and software facilities are described and the furnace control performances using the Model Reference Adaptive Control Algorithm are reported.

PROCESS DESCRIPTION

The phosphate drying furnace is mainly constituted of the following components (fig.1) :

- Feeding system.
- Combustion chamber.
- Drying tube
- Dusting chamber
- Ventilator and chimney.

These elements are described in the following.

Feeding System.

The main part of the feeding system is a constant speed moving belt that carries the raw phosphate into the furnace. A large container spreads the phosphate over the belt at regulated rate by controlling the opening of the container to the belt. This will allow the phosphate to be fed into the furnace at the rate needed for production.

Combustion Chamber.

The combustion chamber produces the hot gas needed for the drying process. The heavy fuel is initially heated to 100° C by steam. To facilitate its mixing with the air, the fuel is pulverised by the aid of auxiliary jet of steam. The necessary oxygen for the combustion is produced by the primary air injected under low pressure by a ventilator in the combustion chamber. The heat produced is transfered into the drying tube by secondary air current.

Drying Tube.

This is an horizontal tube of 25m length, its rotation velocity is constant ; its production capacity is in the order of 150 ton/hr. The tube has cascades in its inner side arranged helically, to facilitate the thermal exchange between the hot gas and the phosphate, and also they help in driving the phosphate to the output of the tube. Contrary to cement furnaces the movement of the phosphate and the hot gas occurs in the same direction in the drying furnace, from the combustion chamber to the dusting chamber.

Dusting Chamber.

The dusting chamber is made up mainly of shelved tubes whose primary function is to slow down and recapture the phosphate fine particules which are carried into the dusting chamber by the hot gas. These fine particules make up about 30% of the dried phosphate.

Ventilator and Chimney.

The main role of the ventilator is to create a reduction in the pressure at the head of the drying tube to induce a secondary air current and to prevent trapping of the phosphate in the drying tube. The chimney action will serve as evacuator of the hot gas out of the furnace.

The final product is received at the exit of the dusting chamber by the main conveyor.

The existing conventional control loops on the phosphate dry process are shown in figure 1.

The flows of primary air and steam are adjusted with respect to the fuel flow in order to ensure a complete combustion.

PROCESS MODEL

Several models have been developed in (K. Najim and all, 1976,1977,1978,1979) to describe the dynamic behaviour of the phosphate drying furnace. We have chosen a single input-single output one, by letting the product feed rate to be kept constant (e.g. maximum production). The fuel flow (the control variable) and the humidity of the dried phosphate (the output variable) are the key variables for suitable single input - single output model of the furnace. A simple representation of the simplified model can be written as :

$$A(q^{-1})y(t) = q^{-d}B(q^{-1})u(t) + w(t) \qquad (1)$$

with

$$A(q^{-1}) = 1 + a_1 q^{-1} + a_2 q^{-1} + \dots + a_{n_A} q^{-n_A}$$
$$B(q^{-1}) = b_o + b_1 q^{-1} + \dots + b_{n_B} q^{-n_B} \; ; \; b_o \neq o \qquad (2)$$

where

$\{q^{-1}\}$ is the backward shift operator, $\{d\}$ represents the process time delay, $\{u(t)\}$ and $\{y(t)\}$ are the process input (the fuel flow) and output (the humidity of the dried phosphate) respectively, and $w(t)$ is a bounded disturbance.

This model is most adaptable to adaptive control system which we have adopted. Moreover, it uses the variables to which the operating of the furnace is the most sensitive.

The sampling period T and the process time delay have been determined from an a priori characterization study of the process, while the process model order has been chosen to allow satisfactory performances of adaptive control system. The obtained values are :

$T = 45s$; $d = 2$; $n_B = 1$; and $n_A = 3$

PRESENTATION OF ADAPTIVE CONTROL SCHEME

We will use the notation of (Landau, Lozano,

1981) and give only a brief outline of the basic theory of the control scheme adopted.

The theory and design of this scheme is widely discussed in the above reference.

The main objective of the control system is to find a control law so that an initial error between the plant output (described by the equations (1) and (2) and assumed to be a minimum phase plant) and a reference sequence $\{y^M(k)\}$ or an initial output disturbance convergence to zero with the dynamics of the C_R - polynomial, i.e.,

$$C_R(q^{-1})(y(k+d)-y^M(k+d)) = S(q^{-1})w(t) \quad (3)$$

where

$$C_R(q^{-1}) = 1+C_1^R q^{-1}+\ldots+C^R_{n_{C_R}} q^{-n_{C_R}} \quad (4)$$

is an asymptotically stable polynomial and the polynomial S is so that :

$$S(q^{-1})\ w(t) = 0 \qquad \text{for } k \geq k^{*} \quad (5)$$

The reference sequence can be realized by the output of a reference model described by :

$$C_T(q^{-1})y^M(k) = q^{-d}D(q^{-1})u^M(k) \quad (6)$$

where

$$C_T(q^{-1}) = 1 + C_1^T q^{-1} + \ldots + C^T_{n_{C_T}} q^{-n_{C_T}} \quad (7)$$

is an asymptotically stable polynomial and

$$D(q^{-1}) = d_o + d_1q^{-1}+\ldots+d_{n_D} q^{-n_D} \quad (8)$$

An appropriate control configuration used for the case of known plant parameters to realise the objectif (3) is given by

$$u(k) = \frac{C_R(q^{-1})y^M(k+d)-R(q^{-1})y(k)}{B(q^{-1})S(q^{-1})} \quad (9)$$

where the polynomials $S(q^{-1})$ and $R(q^{-1})$ verify the following identity.

$$C_R(q^{-1}) = A(q^{-1})S(q^{-1})+ q^{-d}{}_R(q^{-1}) \quad (10)$$

where

$$S(q^{-1}) = 1+S_1q^{-1}+\ldots+s_{n_s} q^{-n_s} \quad (11)$$

$$R(q^{-1}) = r_o+r_1q^{-1}+\ldots+r_{n_R} q^{-n_R} \quad (12)$$

which has an unique solution for the polynomials $S(q^{-1})$ and $R(q^{-1})$ for a given $C_R(q^{-1})$ if one chooses :

$$n_s = d-1$$

and

$$n_R = \text{Max}(n_A-1, n_{C_R}-d) \quad (13)$$

The control law (9) can be written :

$$P^T\phi(k) = C_R(q^{-1})y^M(k+d) \quad (14)$$

where

$$\phi^T(t)=[u(t),u(t-1),\ldots,u(t-d-n_B+1),y(t),\ldots, y(t-n_R)] \quad (15)$$

$$P^T = [b_o, b_o s_1+b_1,\ldots,b_{n_B} s_{d-1}, r_o,\ldots r_{n_R}] \quad (16)$$

When the plant parameters are unknown the parameter vector p of the control law (14) given by Eq(16) can not be computed. Landau and Lozano have developed an extension of the linear controller design given by Eq(14) which is applicable to minimum phase plants and for which only the time delay {d} and upperbounds of the degrees of polynomials $A(q^{-1})$ and $B(q^{-1})$ denoted n_A and n_B are known.

The parameter p in Eq(14) is replaced by adjustable parameter vector $\hat{p}(k)$ which will be updated by the adaptation mechanism.

Therefore the control law is given by :

$$\hat{p}^T(k)\phi(k) = C_R(q^{-1})y^M(k+d) \quad (17)$$

and the design objectif (3) will be asymptotically achieved if :

$$w(k) = 0 \quad (18)$$

and if the following adaptation algorithm is used :

$$p(k) = p(k-1) + F(k)\phi(k-d)\gamma^{*}(k) \quad (19)$$

with

$$F(k+1)= \frac{1}{\lambda_1(k)}\left[F(k)- \frac{F(k)\phi(k-d)\phi^T(k-d)F(k)}{\frac{\lambda_1(k)}{\lambda_2(k)}+\phi^T(k-d)F(k)\phi(k-d)}\right] \quad (20)$$

where

$$0<\lambda_1(k) \leq 1\ ;\ 0<_2(k)\leq 2\ ;\ F(1)>0 \quad (21)$$

and $\gamma^{*}(k)$ is the adaptation error defined as :

$$\gamma^{*}(k) = \frac{H_1(q^{-1})}{H_2(q^{-1})}\varepsilon^{*}(k) \quad (22)$$

where $H_1(q^{-1})$ and $H_2(q^{-1})$ are asymptotically stable monic polynomials and should be chosen such that the transfer function

$$H(z^{-1}) = H(z^{-1}) - \frac{1}{2} \quad (23)$$

is strictly positive real function with

$$2 > \lambda \geq \text{Max}(\lambda_2(k)) \quad \text{for } k_o < k < \infty \quad (24)$$

and $\varepsilon^{*}(k)$ is the augmented error defined as :

$$\varepsilon^{*}(k) = [p-\hat{p}(k-d)]^T\phi(k-d) \quad (25)$$

The adaptive control algorithm which has been adopted for the control of the phosphate drying furnace is derived from the previous one for :

$$H_1(q^{-1}) = H_2(q^{-1}) = 1 \quad (26)$$

The positivity condition in Eq (23) is automatically verified and the expression for the adaptation error in Eq (22) becomes :

$$\gamma^{*}(k) = \frac{C_R(q^{-1})y(k)-\hat{p}^T(k-1)\phi(k-d)}{1+\phi^T(k-d)F(k)\ \phi(k-d)}$$

Figure 2 shows the block diagram of the adaptive control scheme.

PRACTICAL ASPECTS OF THE CONTROL SYSTEM

Computer Hardware and Software Facilities.

The DDC computer hardware used for implementing the controller algorithm was based on a D.E.C. LSI-11 microcomputer. The configuration involves a 16 bit microprocessor with the minimum hardware arithmetic facilities, i.e. all integer and floating point multiplication and division performed by software, 64 K memory, dual floppy disc mass storage, console terminal and teletype printer.

The experimental data interface consisted of a 16 channel multiplexed successive approximation A/D converter, 4 D/A converters all with 12 bit resolution and programmable real-time clock counter.

The standard DEC real-time operating system RT-11 was used to develop the programme and to control its execution, using the real-11 Fortran software facilities.

The flowchart of the real-time algorithm with the interface between the process and computer is shown in fig.3.

The Choice of the C_R Polynomial.

The choice of the polynomial $C_R(q^{-1})$ results from a compromise between the tracking error and the control value. Indeed, we have observed that when the tracking error decreases quickly after any perturbation, the control becomes more energetic. In the case of our experiment, the following polynomial

$$C_R(q^{-1}) = 1-0.85q^{-1}+0.25q^{-2}-0.0585q^{-3}$$

has been chosen in order to avoid abrupt changes in the plant output.

"Start-up" of the Control System.

The initialisation of the control system has been done as follows

$$P^T(0) = [0,\ldots,0]$$

$$\phi^T(0) = [UN,\ldots,UN,HN,\ldots,HN]$$

where UN and HN represents the fuel flow and the humidity of the dried phosphate respectively at the operating point

$$F(1) = 1000\ I \quad ; \quad \lambda_1(k) = \lambda_2(k) = 0.95$$

The use of such initial values lead to a control too important for the process this induces us to fix the control to its nominal value UN until the computed control is close to an interval around its nominal value UN and this in constant way (the control may remains in the prescribed interval for about ten iterations). This beeing done, the control system operated with the "decreasing gain" algorithm ($\lambda_1(k) = \lambda_2(k) = 0.95$) as long as the trace of the adaptive gain matrix is greater than a prescribed value. If not so, the control system operated with "constant trace" algorithm ($\lambda_1(k) = \lambda_2(k)$ and $\lambda_1(k)$ is such trace $(F(k)) =$ constant).

Results.

In order to compare the performances of the adaptive control scheme with those achieved when using conventional PID controllers, the following experiments have been carried out

- the PID controllers are used to control the phosphate drying furnace, its parameters are adjusted by an operator in order to provide acceptable performances. The microcomputer is used only to supervise the furnace operating and for production management.
- The adaptive control system presented above is used to control the phosphate drying furnace. The microcomputer is then used to control and supervise the furnace operating and for production management.

The operating conditions of the dryer for both adaptive control system and conventional PID controllers were the most common ones : at the input, the product feed rate was close to 220 t/h and its moisture content was subject to random variations. The range of these variations is between 10 and 15%.

The recorded curves of the humidity of the damp and dried phosphate and the fuel flow obtained by the two experiments are shown in figures 4 and 5.

Table 1 summaries statistical results that allows to appreciate the performances by using the two control systems.

Records	Statistical Characteristics	Conventional Controller	Adaptive controller
Damp phosphate humidity	Esperance	12,3%	12,70%
	Variance	0,18	0,7[illegible]
Dried phosphate humidity	Esperance	1,78%	1,42%
	Variance	0,57	0,15
Fuel flow	Mean consumption	11,38	10,9
	Variance	0,16	0,229

Table 1 Recorder statistical characteristics

CONCLUSION

The control studies reported in this paper demonstrate a successful application of model reference adaptive controller to an industrial phosphate dryer.

The results of the experimentation illustrate the key features of the model reference adaptive controller, especially its potentiality to ensure suitable performances when changes of the plant dynamic characteristics occur.

On the other hand, the adaptive control system presented above allows, an energy saving of 4,5% and satisfactory quality of regulation which involves the material saving, because of less thermic solicitations leading to a longer period between revisions.

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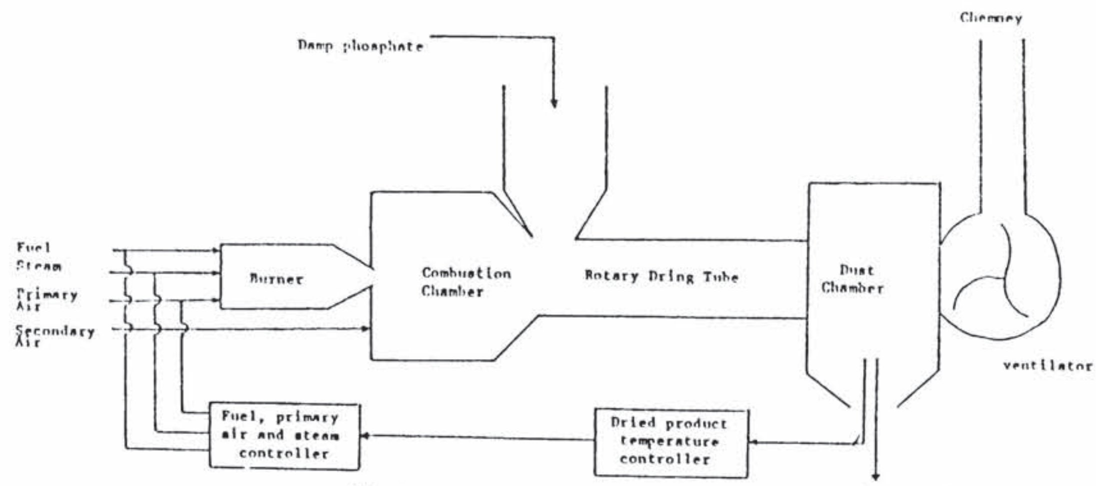

Fig.1 Drying Surface

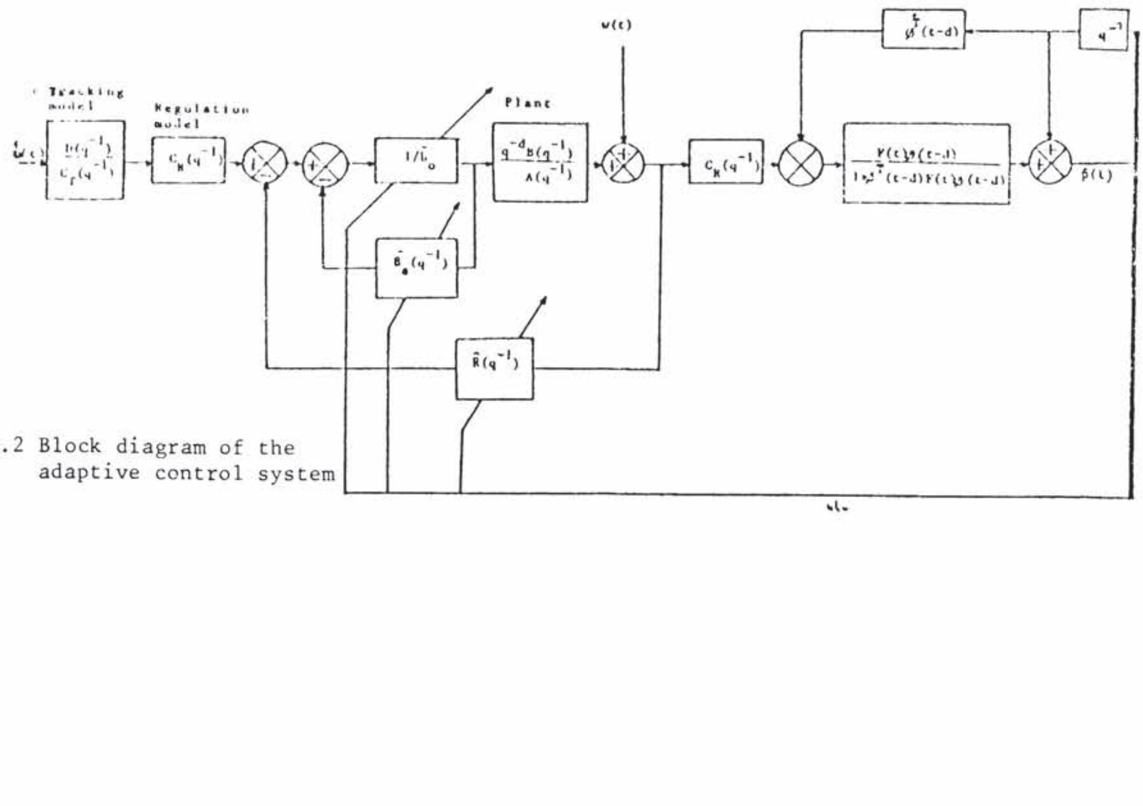

Fig.2 Block diagram of the adaptive control system

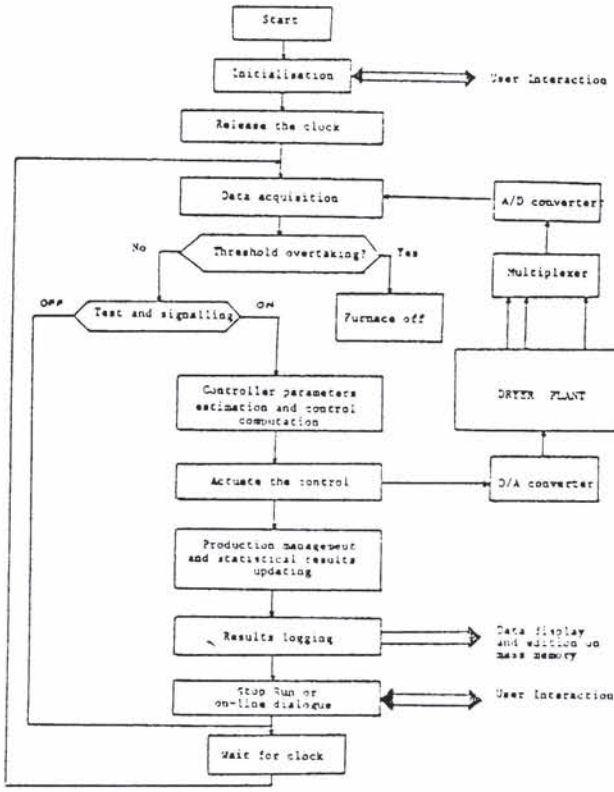

Fig.3 Flowchart of the real-time algorithm

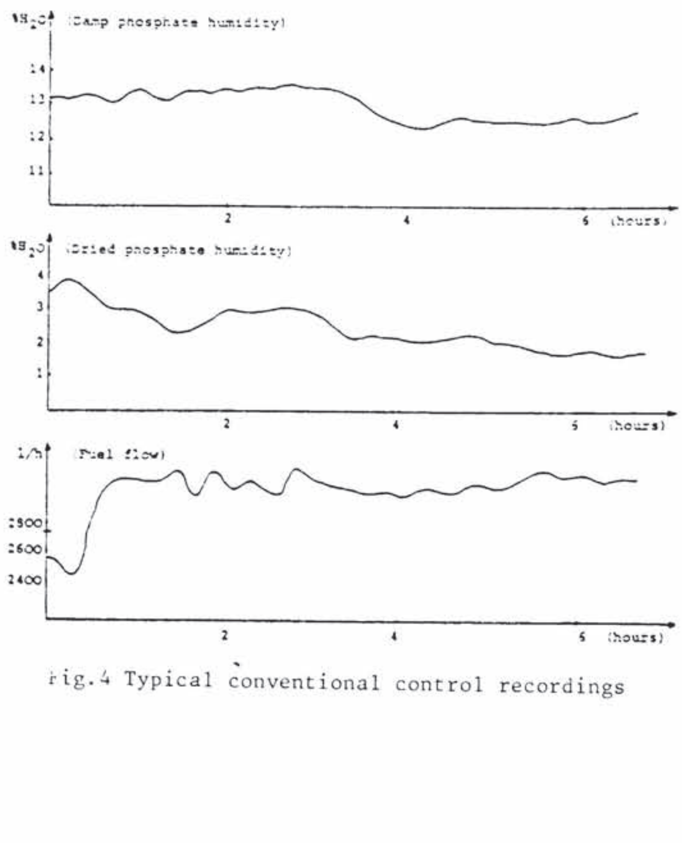

Fig.4 Typical conventional control recordings

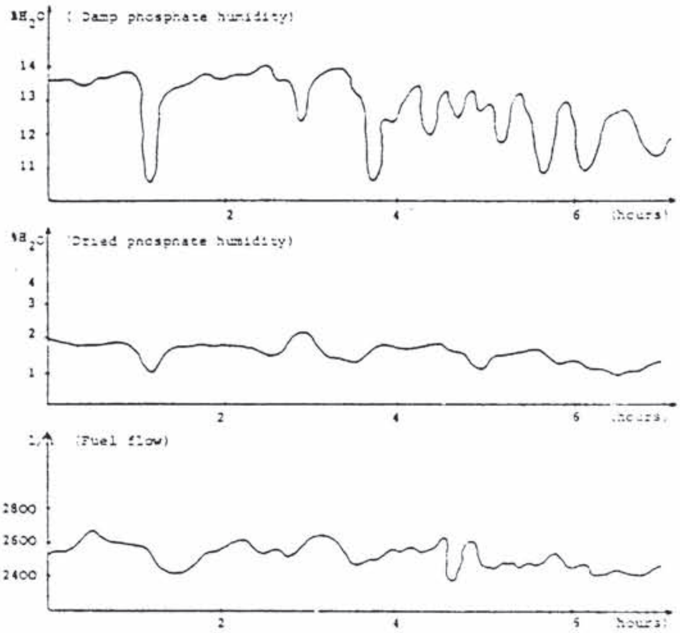

Fig.5 Typical adaptive control recordings