Pergamon

Applied Thermal Engineering Vol. 17, Nos. 8–10, pp. 935–945, 1997

Printed in Great Britain
PII: S1359-4311(96)00078-6
1359-4311/97 $17.00 + 0.00

A HYBRID, KNOWLEDGE-BASED SYSTEM AS A PROCESS CONTROL 'TOOL' FOR IMPROVED ENERGY EFFICIENCY IN ALUMINA CALCINING FURNACES

A. Kontopoulos,* K. Krallis,* E. Koukourakis,* N. Denaxas,† N. Kostis,† A. Broussaud‡ and O. Guyot‡

*Laboratory of Metallurgy, National Technical University, GR-15780, Zografos, Greece, †Aluminium de Grece S.A., 1 Sekeri Street, GR-10671, Athens, Greece and ‡Control International S.A., 1 Avenue de Concyr, BP 6009, F-45060, Orleans, France

Abstract—This paper describes the development and implementation of a hybrid SCADA (Supervisory Control and Data Acquisition) system for the air suspension 'flash' alumina calciner at Aluminium de Grece St. Nicholas plant. The system includes two additional modules, an 'expert system' based on 10 years of commissioning and operating experience and a dynamic model continuously predicting the quality of the product. It is implemented on an industrial PC under an industrial control software environment and interfaces to the furnace through a programmable logic controller (PLC) system. The system guides the furnace operator to reduce sensible heat losses by operating with a marginal excess air flow rate, to take advantage of the higher energy efficiency at higher production rates and, at the same time, to avoid potentially dangerous operating conditions leading to loss of production and consequential energy losses. It also performs the traditional SCADA functions (data acquisition, maintaining history files for important parameters and display of important operating parameters in both a mimic process diagram and a series of graphs.) In addition to these tasks a simplified dynamic model gives the operator a prediction of the current value of the main product quality parameter, which can only be measured with laboratory equipment. Preliminary results have shown that reduction of secondary air flow rate and reduced downtime achieved by the operator under the guidance of the system can reduce energy consumption by as much as 10%. A similar, or even greater, improvement in energy efficiency can be expected by implementing a similar system to cement calcination kilns based on the same technology.

Keywords—Alumina calcination, expert control systems, energy savings.

NOTATION

$[C_i]$	vector of controlled variables
$[M_j]$	vector of manipulated variables
k_{ij}	steady-state 'gain' of C_i vs M_j
τ	first-order time constant
τ_{ij}	first-order time constant of C_i vs M_j
T_c	calcination temperature
F	aluminium hydroxide feed rate
S_{st}	predicted steady-state value of BET specific surface
S_{ins}	predicted instantaneous value of BET specific surface

INTRODUCTION

Evolution of the alumina calcination furnaces

Traditionally, the calcination of aluminium hydroxide to smelters-grade or technical-grade alumina takes place in long rotary kilns. Such units are heavy fuel consumers (3.8–4.5 MJ/kg of alumina or more), while further reduction of heat consumption seems to be very difficult due to the heat losses imposed by the long cylindrical body of the kiln [1].

Alumina producers and equipment manufacturers have focused on the effort of improving the energy efficiency of industrial alumina calciners. A noticeable technological step was the introduction of suspension preheaters [2], a short kiln design with a dry process preheater consisting of various stages of heat exchange in ducts and cyclones, similar to the design of some cement kilns.

This configuration was improved in Japan with the introduction of a special precalcining chamber at the lower section of the preheater.

Lurgi and VAW mention that the introduction of fluidised bed calciners improved the flexibility of process control and—compared to rotary kilns—led to energy savings of up to 35%. However, the attrition of alumina particles and the high maintenance cost are the major disadvantages of this system [2].

Fives-Cail Babcock (FCB) [2, 3], based on its experience in suspension preheaters in cement kilns, developed a flash calcining flow sheet to treat ores or mineral with particles size of 1 mm or less. The core of this process is a stationary cyclone-like calcining furnace, with an associated gas–solid separation cyclone. The successful operation of a 1.7 mt/h pilot-plant led to a contract for the construction of a 950 mt/day static unit at the Aluminium de Grece (ADG) St Nicholas alumina plant. Advantages of the FCB flash calciner are summarised as a reduction in capital costs, reduction in fuel and electric power consumption, better utilisation flexibility in terms of production rate and product quality control.

The ADG flash calciner has been in operation since 1984 and it is the first of its type ever built. Its nominal capacity is 950 mt/day, but with appropriate manipulations the daily production of calcined alumina can be increased to 1000–1100 mt/day. The heat consumption is about 3.1 MJ/kg of calcined alumina [3]. Figure 1 presents the total specific fuel consumption on annual basis for the years 1980–1992. It is obvious that the installation of the flash calciner furnace resulted in significant lower energy consumption. After 10 years of flash calciner operation, engineers and operators now possess the necessary experience and knowledge for assisting in the hybrid expert system development.

Crucial characteristics of calcined alumina

The physicochemical properties of calcined alumina affect the quality of the final product, i.e. the aluminium produced by the Hall–Heroult cells, as well as the electrical energy consumption at the electrolysis cells. The calcination process of alumina hydroxide mainly affects the following important properties of alumina [4, 5]:

1. Silicates content (SiO_2%). The SiO_2 content is produced by the silica-based refractory lining of the calciner. The quality of the refractory lining, the geometric characteristics of the furnace, as well as the frequency of thermal shocks originating from abnormal operation (shut-down, start-up), play a significant role in the enrichment of alumina with SiO_2.

2. Particles size distribution (μm). The fines content (-45 microns) is an important property of the alumina. In order to prevent dusting problems in aluminium production cells, the fine particles (-45 μm) should be kept below 10%.

3. Specific surface (m^2/g). The BET specific surface of calcined alumina is in very closely relation to the reactivity of the alumina with fluoride ions and, consequently, to its solubility in the cryolite

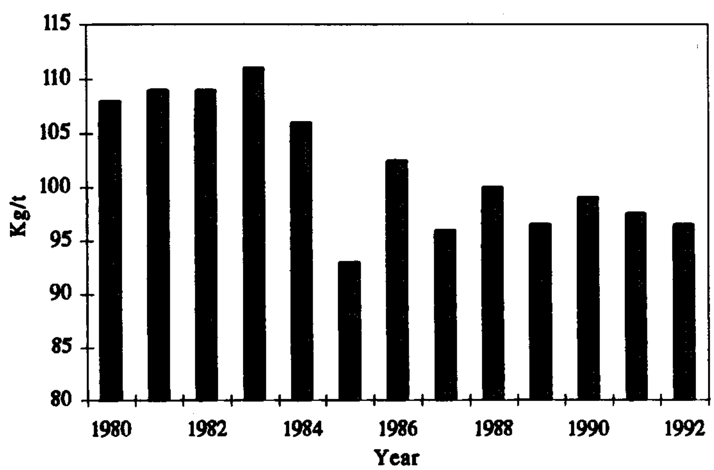

Fig. 1. Annual fuel oil consumption of the flash calciner.

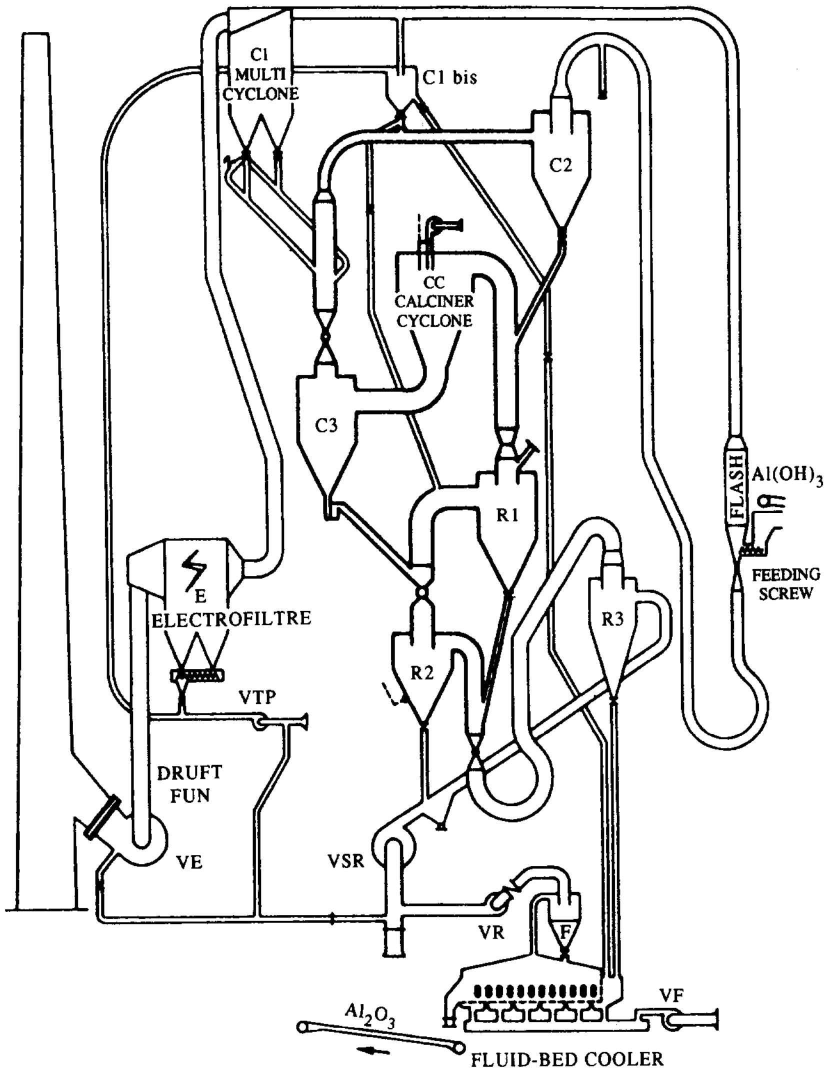

Fig. 2. Simplified flowsheet of the calciner.

bath at the aluminium electrolysis cells. The specific surface area depends on the porosity of the alumina formed by the elimination of crystallic water during calcination. If the calcination temperature exceeds certain limits, porosity disappears and transformation to α-Al_2O_3 takes place. The surface area decreases with the increase of the α-Al_2O_3 content because of the α-Al_2O_3 crystal growth process. The ADG flash calciner can produce alumina qualities ranging from 45–80 m^2/g. This parameter is usually kept within the 65 ± 3 m^2/g range.

4. α-Al_2O_3 content (%). There exist practical limitations relating to the alpha alumina content. The calcined alumina contains no more than 3–5% of α-Al_2O_3 for a standard BET surface [6].

Description of the ADG/FCB flash calciner

A simplified diagram of the process is shown in Fig. 2. The wet aluminium hydroxide feedstock, produced by the Bayer process, enters via a screw feeder to a flash dryer, which consists of a long vertical air duct. The wet solids (with 5–8% humidity content) are entrained by a stream of relatively hot waste gases which enters from a venturi constriction at the lower part of the installation. The fine solids remain in suspension and they are dried quickly before they enter into a two-section multicyclone (C1). The gases and a small amount of fines are carried to the electrofilters. The clean waste gases are drawn by a large blower (VE) to the chimney.

The solid underflow of C1 is entrained by the hot combustion gases and precalcined to 320–350°C for a short time in cyclone C2. The gas leaving C2 is fed to the flash dryer, while the preheated solids, entrained by the secondary combustion air, are fed tangentially to the main calcination chamber (CC).

At the top of CC there are three burners, where preheated heavy fuel oil and the primary combustion air are fed to the combustion zone. A high heat transfer coefficient between gases and solids is achieved in the swirling flow. The calcination of aluminium hydroxide is described by the following equations:

$$2Al(OH)_3 \rightarrow \gamma - Al_2O_3 + 3H_2O\ (g)\ \ \Delta H^0_{298} = -94991\ \text{kJ/kmol}$$

$$\gamma - Al_2O_3 \rightarrow \alpha - Al_2O_3\ \ \Delta H^0_{298} = +22\,183\ \text{kJ/kmol.}$$

The hot gases and solids leaving the CC enter cyclone C3, where the calcination reaction is completed and the two phases are separated. The hot waste gases (approximately 1000°C) are used to entrain the uncalcined feedstock into cyclone C2. The hot calcined solids are collected from the bottom of C3 (with a special siphon) and then passed to a system of three cyclones (R1, R2, R3), where their sensible enthalpy is recovered by heating the secondary combustion air.

The excess heat content of the calcined solids leaving R3 (280–300°C) is removed by water in a fluidised bed cooler (FBC). The fluidisation air is supplied by the VR blower and, after leaving FBC, it is separated from dusts in a small cyclone (F) and then, via the VF blower, supplements the secondary combustion air in the suction duct of blower VSR. The fine particles of alumina hydroxide collected by the electrofilters are also transported by a small air flow into the main calcination streams.

The operator of the calciner has a detailed indication of the furnace conditions through the existing traditional control panel. A number of paper recorders and indicators provide information about the temperature profile, pressure drop, flow rates of gases, feedstock and fuel oil and waste gases analysis. There is also a large number of alarms giving warnings about most malfunctions occurring along the whole furnace installation.

The existing control system consists of a set of two analogue PID controllers in cascade, which control the calcination temperature by adjusting the fuel flow rate. The operator can also control the secondary air flow (VSR) and the rotation speed of the extractor fan VE. In addition, the feedstock flow rate can be adjusted to the desired value by a hydraulic coupler used for the manual control of the screw feeder's speed.

BASIC STUDY OF ALUMINA CALCINATION

In order to build the hybrid knowledge-based expert system, a complete set of heuristic rules, together with a 'deep' knowledge base were to be developed. Heuristic rules were the main advisory tool (diagnosis of certain malfunctions), while deep knowledge provided the operator with a set of optimum values for the parameters that could be adjusted via the control panel, so that best energy efficiency and better product quality characteristics were achieved. The deep knowledge involved thorough understanding of the process in the form of mathematical models and could be used for prediction of the unknown or unmeasured parameters. The methodology for the design and implementation of the dynamic model of the process involved the following areas.

Correlation of historical plant data

In order to prepare a complete picture of the ADG furnace present status, the ADG team conducted a preliminary evaluation of the historical data pertaining to the operation of the flash calciner. Two graphs showing the behaviour of specific fuel consumption of the calciner as a function of aluminium hydroxide feed rate and calcination temperature are presented in Fig. 3 and Fig. 4 (without specific values). From these data sets it was found that the specific fuel consumption can be closely approximated with a second-degree polynomial. It is obvious that specific fuel consumption increases at lower production rates.

Steady-state response tests

In order to identify the important and interactive process parameters a 1/2 fractional factorial test for four variables was applied. For this purpose, a list of manipulated variables (adjustable

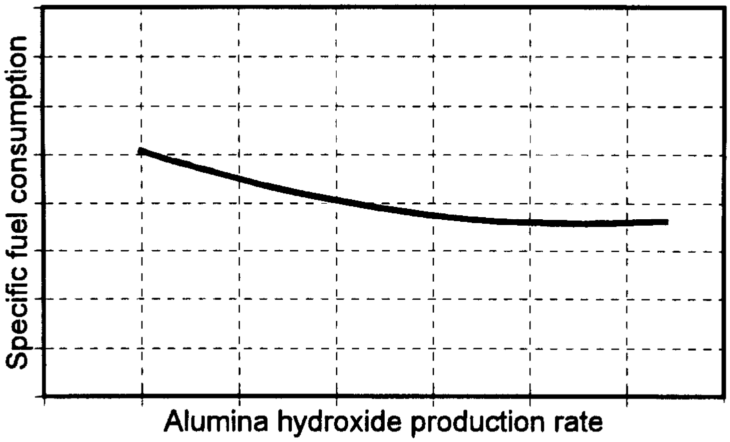

Fig. 3. Specific fuel consumption vs production rate.

by the operator from the control panel instruments), controlled variables (to be optimised by the system) and disturbances (not controlled or predicted) was defined.

Manipulated variables could be adjusted by the operator from the control panel, either directly or indirectly (as a combination of other parameters). A step change of the manipulated variables was induced in each test and the exact values of these changes were chosen to satisfy the needs of safe operation and maximum production rate. Controlled variables were the important ones as they affect product quality characteristics and energy efficiency of the flash calciner. The specific surface area (BET value) was the most important of the controlled variables because it characterised the quality of the calcined alumina. The set of manipulated and controlled variables, as well as the disturbances of the process, were the following:

Manipulated variables
- Calcination temperature
- Speed of VE blower motor
- Total secondary air flow (at VSR suction)
- Aluminium hydroxide feed rate (wet mt/h)

Controlled variables
- Temperature profile
- Pressure profile
- Product quality parameters

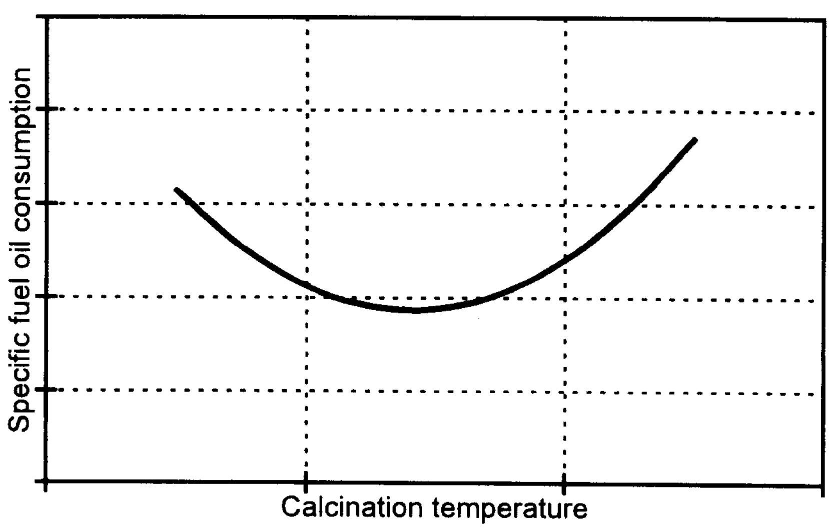

Fig. 4. Specific fuel consumption vs calcination temperature.

Excess air (% O_2 in waste gases)
Carbon monoxide content of waste gases

Dynamic response tests

In order to develop a simplified dynamic model, a series of four tests was performed. The interpretation of the results was based on the assumption that a first-order dynamic response connects each controlled variable C_i to each manipulated variable M_j and that the effects of each controlled variable are independent of those of the others. The dynamic response was expressed in the form of a set of Laplace equations connecting manipulated and controlled variables, which, in matrix form, can be written as

$$[C_i] = [A_{ij}]\cdot[M_j]$$

$$A_{ij} = \frac{k_{ij}}{1 + s\tau_{ij}}$$

First-order time constants were extracted from the recordings provided by the control panel pen recorders.

The results of the above study are summarised as follows:

1. Energy effieciency is mainly affected by the excess air required to stabilise operation of the furnace. As expected, operation near the nominal production rate is more energy efficient than operation at lower production rates.
2. Product quality is defined mainly by the specific surface (BET) and the α-alumina content of the product.
3. Only the specific surface is very sensitive to the process parameters. The α-alumina content is nearly always within specifications.
4. An additional quality feature is the absence of silicates. The presence of SiO_2 is an indication of maintenance requirements of the refractory lining of the furnace.

DEVELOPMENT OF THE CONTROL SYSTEM ELEMENTS

Development of the rule base

For the presentation of the synthesis of process control objectives, the goal-tree–success-tree (GTST) model [7] was used. The GTST model is a hierarchical formulation of a set of goals which must be realised in order to meet the control system objectives. The goal tree is constructed by definition of the root goal as a single unambiguous statement of the primary objective of the problem solution. The single goal is then decomposed into subgoals which are then similarly decomposed into subgoals and so on, until no further decomposition is feasible. The goals of the lowest level of the tree are satisfied by any one of the action routes called success paths which lie below them.

The GTST model represents the knowledge for the problem solution and can be directly translated into the knowledge base for the expert system. A detailed GTST model was developed for the ADG flash calciner composed of model parts. Each of them analysed one objective of the calciner operation. The overall GTST model of the flash calciner is illustrated in Fig. 5.

The rules comprising the knowledge base have the typical form:

IF condition – 1[and/or condition – 2...] THEN action – 1[and action – 2...].

The condition part of rules made reference to particular measured variables and in many cases to trends or thresholds of measured values. The action part was executed when the if part was true and the result of this action was passed to the operator through an advisory or warning message.

Six subsets of rules have been formed so far concerning:

A: Prediction of malfunctions at the flash calciner
B: Adjustment of BET value
C: Control of the aluminium hydroxide feedrate
D: Control of the secondary air flow rate (at VSR suction)

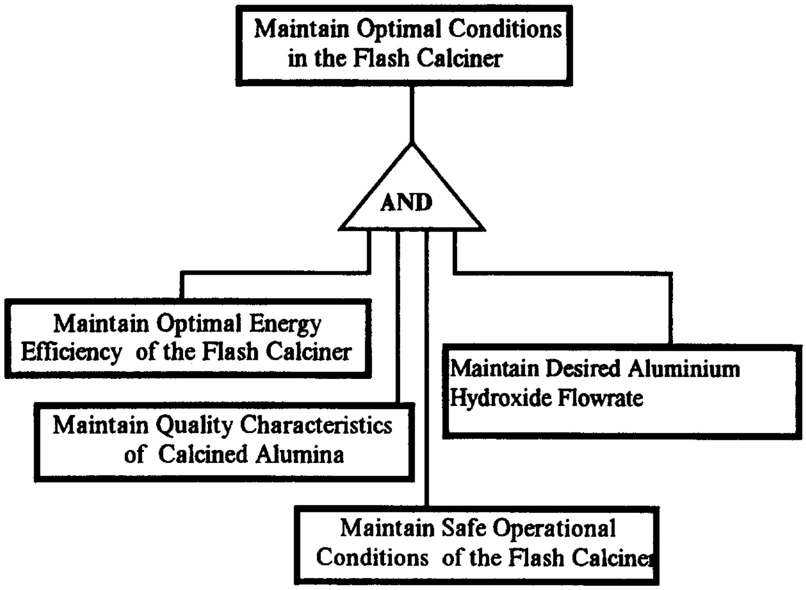

Fig. 5. Top level goal-tree–success-tree.

E: Control of rpm at VE motor
F: Confirmation of oxygen meter malfunction

The six groups of rules guided the operator to satisfy requirements of energy efficiency and product quality while keeping the system within safe operating limits.

Definition of control strategy

During the base study of the process and after discussions with the most experienced operators and supervisors, the main causes of abnormal operation were identified. On this basis a strategy for process control was defined Fig. 6 and is detailed below.

Although the task of maintaining normal and safe operation of the flash calciner involved many different activities, four of them were considered by the system:

1. Keeping the combustion chamber in subatmospheric pressure. This requirement was satisfied by proper adjustment of the secondary air flow rate (at VSR fan) in combination with the rotational speed of the extractor fan VE.
2. Preventing accumulation of alumina dust and clogging in the ducts. Such problems often arise especially between the preheater cyclone C2 and the flash dryer or between heat exchangers R2 and R3.
3. Avoiding blockage of alumina fine particles at the various cyclone exits. Such problems are difficult to control directly. Operators' experience shows that warning of such problems is the steady and relatively slow change of some of the temperatures which cannot be attributed to other reasons.
4. Reducing sensible heat losses. As was shown by the basic study of the furnace, this requirement is in direct relation with the excess air and feedstock flow rates. The expert system estimated the marginal amount of air needed for safe and normal unit operation and advised the operator to adjust either the secondary air flow rate introduced by VSR fan or the screw feeder's speed.

The combination of all these expert system tasks was a reliable guide for the operators to minimise specific thermal energy consumption while maintaining product quality within acceptable limits, as well as ensuring safe unit operation. This operating policy has already proved to maximise energy efficiency of the furnace while suppressing the influence of most uncontrolled disturbances or unpredictable events.

Dynamic model of calcined alumina BET surface

BET value was predicted by a real-time model based on long-term correlation established from historical plant data. Assuming a first-order dynamic response, the instant BET value S_{ins} at time t_i is

$$S_{ins}(t_i) = S_{ins}(t_{i-1}) + \frac{t_i - t_{i-1}}{\tau}\left[S_{st}\left(t_i\right) - S_{ins}\left(t_{i-1}\right)\right],$$

where τ is the time constant determined by the dynamic response test.

S_{st}, the target value for BET, was recalculated from a multiple linear regression as a function of feedstock flow rate F, calcination temperature T_c and regression coefficients a, b and c, every time the operator entered a new BET value:

$$S_{st}(t_i) = a - b \cdot F - c \cdot T_c.$$

DESCRIPTION OF THE CONTROL SYSTEM

For the purposes of this project additional data acquisition hardware has been installed which consisted of an Allen Bradley PLC 5/25, with 13K RAM. The PLC modules were connected to sensors measuring the process parameters. The PLC received 28 analogue measurements; 14 of them corresponded to temperature measurements, 6 to pressures, 4 to flow rates, 2 to oxygen and carbon monoxide sensors and 1 to the rotation speed of VE.

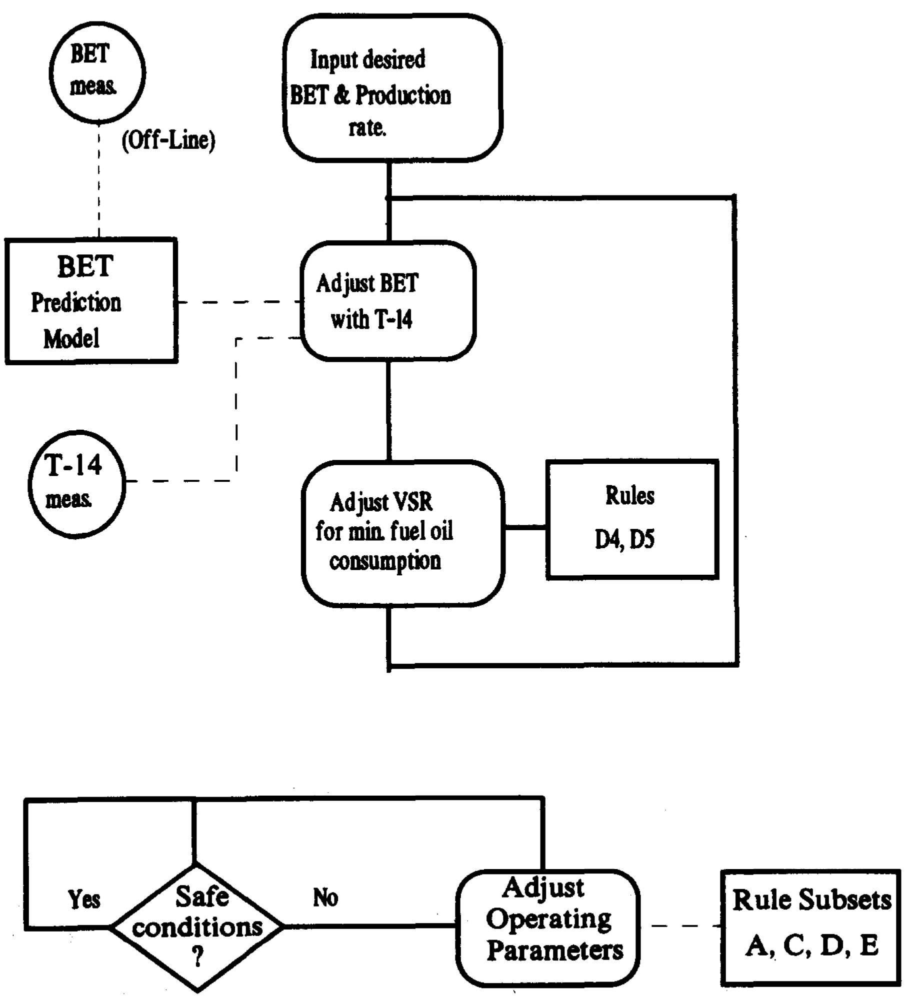

Fig. 6. Control strategy flow sheet.

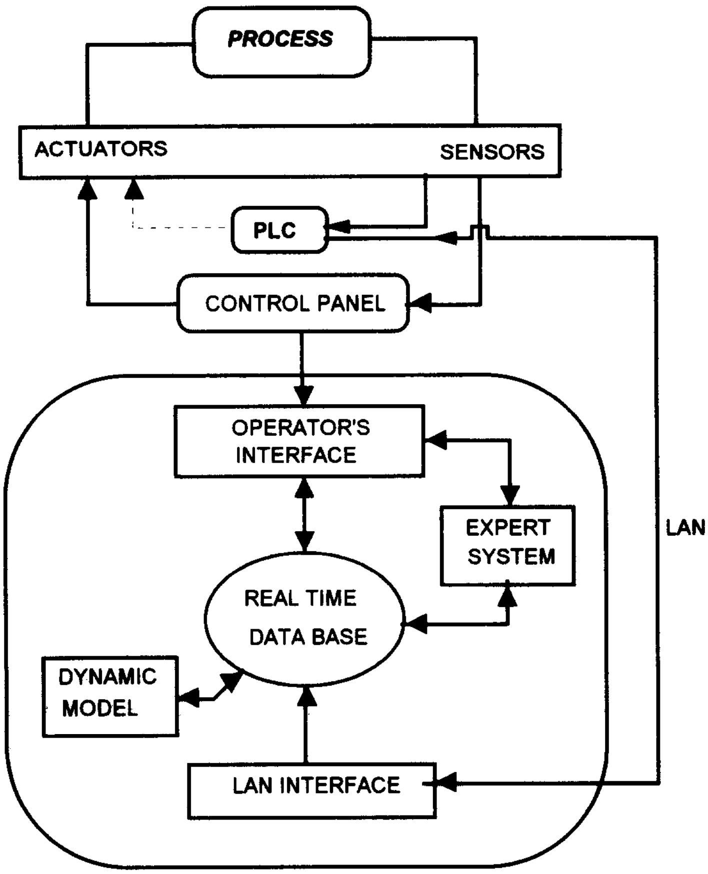

Fig. 7. Structure of the control system.

The data acquisition module communicated with an industrial PC based on an Intel 80486/66 MHz processor over a DH + (Data Highway Plus) industrial LAN. The operating system selected was the IBM OS/2 (Version 2.1 with the Greek fonts), which offered a real-time, multi-tasking environment and a user-friendly interface. For the implementation of the real-time database, operator's interface and data acquisition software modules, ONSPEC 4000 (developed by Heuristics Inc., USA) was selected, as it offered facilities required to implement the expert system. The software structure of the hybrid knowledge-based control system is illustrated in Fig. 7.

The most important modules of the system were:

1. LAN interface module receiving process instrumentation signals from the PLC.
2. Control software module, including the SHADOW real-time database.
3. Expert system module implementing the control strategy. ONSPEC includes ONEVENT, a module for developing the expert system. It used ONTALK language (a derivative of SMALTALK object-oriented language) for writing the rules. The rules were processed in real-time using ONEVENTP (ONEvent Processor) program which scaned the rule base and decided which rules should be triggered.
4. Real-time dynamic model of the process which predicted the BET value and assisted the expert module in building qualified conclusions. The dynamic model for BET prediction was implemented in a custom module, FFCDYN accompanied by a BETMOD module which handled all intermediate calculations needed for the BET prediction. The BETMOD module used record files to store measured and predicted BET values.
5. Estimation module handling logic decisions tables, evaluating formulas, etc.
6. Statistical process control module (SPC). The expert system, as well as other system modules, required parameter change rates (trends), mean values, standard deviations, etc., instead of actual raw values. This was implemented as a custom module, STATS.

7. User-friendly graphical interface for communication between the system and the operator or the engineer. The interface provided a mimic diagram of the process. Both screens contained indicators and alarm signals which informed the operator about the current status of the unit. Some utility screens have also been designed for giving information about important derived parameters, such as specific fuel consumption and predicted BET value.

Furthermore, the operator interface had real-time and historical data trending capabilities. This task was performed by the ONVIEW/Supertrends module. Five windows were used to display all important measurements (temperatures, pressures, flow rates or calculated values of BET, excess oxygen, specific fuel consumption, etc.) in real-time.

RESULTS AND DISCUSSION

The system was accepted favourably by the operators of the furnace, although few of them had been trained on it before a series of formal training sessions were organised, in parallel with performance monitoring.

The first semester of 1995 was the evaluation period and results obtained during this period were compared with the same period in 1993. The absolute figures of the parameters studied are treated as confidential by Aluminium of Greece S.A. and cannot be published, so only the relative changes will be discussed.

Comparison of specific energy consumption per ton of product averaged over a 30-day period showed consistently a decrease of 3–10%. The improvement still depends on the operator, as some operators make better use of the messages presented by the system. At the same time the stability of operation has been improved and prolonged operation near the maximum capacity (950–1000 t/h) has been achieved.

The number of alarms from the system were, during normal operation, 1–3 per day. Of these, 1–2 messages guided the operator to set the air flow rate to an efficient value, while the remaining were related to dust blockages and other safety-related events. Additionally, during the summer months, a number of alarm messages related to overheating of the closed water-cooling system were received.

The product quality has also improved, and samples with BET specific surface out of the desired range have been greatly reduced without increasing the burden of sampling and analysing samples of the operator. With three samples per day the on-line quality model gave a reliable indication, except during start-up periods. In the past 5–6 samples per day were analysed, which imposed a heavy burden to the operator, without offering him the advantage of continuous indication during minor changes of feed rate or temperature.

CONCLUSIONS

This project demonstrated that it is possible, by using modern knowledge-based control techniques, to facilitate optimum operation of major thermal installations, and specifically furnaces involving air suspension of the feedstock in the combustion area.

Such systems can assist operators to have their best performance, while reducing the burden of keeping watch on large and complicated control panels.

As these systems can communicate easily over long distances over computer networks, they could allow more centralised control of a number of units from one location; this possibility is currently being investigated.

REFERENCES

1. N. S. Shmorgunenko, G. V. Telyatnikov and T. A. Arlyuk, An investigation on how the equipment flow sheet for the calcination process influences the physicochemical properties of alumina used for electrolysis. In *Light Metals* 1985, Edited by H. O. Bohner. The Metals Society, New York (1985).
2. J. P. Henin and A. Lectard, Suspension flash calcining. *Engineering and Mining J.*, October, 77 (1993).
3. N. Denaxas and A. Zervos, Saving energy in alumina–aluminium plants. In *Energy Efficiency in Process Technology*, Edited by P. A. Pilavacci. Elsevier Applied Science, London (1993).

4. S. Hamano, T. Furubayashi, O. Yamanishi and K. Yamada, Properties of smelting grade and specialty aluminas. In *Light Metals* 1991, Edited by E. Rooy. The Metals Society, New Orleans (1991).
5. G. N. Gopienko and N. S. Siraev, An effect of the alumina quality on aluminium electrolysis. In *Light Metals* 1985, Edited by H. O. Bohner. TMS, New York (1985).
6. A. Pinoncely and K. Tsouria, *Light Metals* 1995. The Metals Society, Las Vegas (1995).
7. M. Modarres and T. Cadman. A method of alarm system analysis for process plants. *Computers Chem. Engng* **10**, 557 (1986).