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Tel. +33 1 53 93 05 00 - Fax +33 1 53 93 05 45/47 - ifa@fertilizer.org - www.fertilizer.org

OPERATING EXPERIENCE WITH RULE-BASED CONTROL OF THE CAN/NPK GRANULATION

P. Bo Olsen and K. Sorth
Kemira Denmark, Denmark

1. INTRODUCTION

Controlling the granulation process, in the fertiliser industry, is usually a very operator-dependent process in terms of both quality and yield. An obvious approach to control the process is to establish an automatic system, and in that way minimize the number and size of fluctuations in the process.

When seeking a higher degree of automatic control of the granulation process the usual approach has been to establish a mathematical model of the process. However, experience indicates that mathematical process models either become too simple to be of any practical value, or too comprehensive and integrated into a specific process to possess any general applicability.

There is a striking contrast between the difficulties encountered in establishing adequate mathematical descriptions of the granulation process on the one hand, and on the other hand the relatively easy way by which human beings can be trained and, in a relatively short time, become skilled operators.

When seeking this automatic control an alternative approach is to use Fuzzy logic (See the appendix for a short introduction to the Fuzzy theory) which is based on the concept of modelling the way the operators make their decisions, in other words, to model the operators' thinking.

In the case of Kemira Denmark the fertiliser granulation process is a spherodizer operation.

The development of the Fuzzy Controller was initiated by Kemira Denmark A/S, and developed in close collaboration between the Danish company PROCOS A/S and Kemira Denmark A/S. The implementation of the controller was started in May 1990. After two years the Fuzzy Controller concept has, reached a very high level of robustness and acceptance among the operators which makes it possible to have an on-line time of the Fuzzy Controller close to 90%.

Today the Fuzzy Controller has the capability of handling major disturbances in the process far beyond the expectations at the start of the project.

2. THE CAN/NPK FERTILIZER MANUFACTURING PROCESS

2.1 Process Overview

At Kemira Denmark A/S CAN and NPK production is based on spherodizer technology.

A fertilizer slurry is made by feeding different solid and liquid raw materials into a reactor system with several reactors in a series.

Together with process parameters such as pH, temperature and water content, the type and amount of raw materials are specified and controlled for each fertilizer recipe.

The slurry is atomised by mixing with compressed air, and sprayed on a curtain of existing undersize granules in the front of the spherodizer. The slurry particles cover the surface of the granules and give incremental growth to the diameter of these by layering.

FERTILIZER GRANULATION AND GROWTH THROUGH THE FLUIDIZED BED DRUM TECHNIQUE - EXPERIENCE AND INDUSTRIAL RESULTS IN THE LATEST UNITS BUILT

E. Vogel
Kaltenbach-Thuring, France

ABSTRACT

The fluidized drum granulation process (FDG) is a combination of a drum granulation and a fluidized bed fitted inside the drum.

The granulation drum is fed with seeds which may be either recycled products, or prills or possibly compacted products to be rounded.

The granulation drum combines growth and cooling or drying operations, as the case may be.

The process was implemented at an industrial scale in 9 plants with a capacity ranging from 300 to 1100 tpd.

The paper deals with actual application cases:

- Urea granulation and growth,
- Nitrate growth,
- Ammonium sulphate growth,
- Rounding of PK or NPK compacted products.

In each of the above mentioned cases, references will be given as well as basic data such as granule size curves, properties of finished products, operational conditions, etc.

The damp granules are transported through the rotating spherodizer and dried by a cocurrent flow of heated air.

The dried fertilizer granules are fractionated into oversize, final product and undersize. Oversize is crushed and recycled to the spherodizer with undersize granules.

Final product is cooled and coated before storage.

The spherodizer process has considerably varying time delays, and there is a very close connection between mass- and heat-balance over the spherodizer.

An outline of the spherodizer-loop is shown in figure 1.

2.2 Controlling the Spherodizer Process

2.2.1 Control Problems

The spherodizer process is characterized by time varying non-linear behaviour, and relatively few measurements are available. Consequently, automatic control is usually restricted to a few simple control loops on secondary control variables leaving the responsibility for the primary control variables to the spherodizer operator.

The performance of the spherodizer is influenced by changes in several different parameters:

Slurry
- Chemical composition
- Water-content
- Temperature
- pH
- Viscosity

Spherodizer loop
- Nozzle performance
- Air temperature
- Air flow
- Scaling in spherodizer
- Performance of screens
- Performance of crusher
- Recycle influence, e.g. amount, granulometry and temperature
- Operator influence, e.g. experience and awareness

2.2.2. The Secondary Control

The secondary control is carried out by PID-controllers (PI-mode) in the Process Control System.

The following variables are kept constant at a set point by the PID-controllers:

- slurry flow into spherodizer,
- air pressure on atomization nozzles,
- temperature on inlet air,
- amount of recycled material.

2.2.3. Primary Control

The first three of the four variables mentioned in the above section are the main variables for the primary control conducted by the operator. The primary variables for the operator to control are:

- outlet air temperature,

- screen analysis of product leaving the spherodizer.

The operator alters the temperature of the outlet air by changing the set point on the PID-controller, which keeps the inlet air temperature constant, and/or by changing the set point on the PID-controller, which keeps the flow of the slurry constant. The operator changes the screen analysis in the same way by changing the set points on the air pressure and on the slurry flow.

Changing the air pressure on the nozzle changes the amount of seeds introduced into the spherodizer, and it changes the incremental growth of the diameter of the existing particles in the falling curtain, too.

Changing the flow of the slurry to the spherodizer changes the outlet air temperature. The direction of the change depends on whether it is a NPK- or a CAN-slurry, and, of course, the incremental growth of the particle diameter is changed.

Changing the inlet air temperature creates changes in the outlet air temperature.

In the process there are three bottle-necks or constraints. These constraints are as follows:

- maximum permitted inlet air temperature,

- maximum possible air pressure on the nozzles,

- maximum available slurry flow.

The primary task for the operator is to increase the production, whenever possible, though still keeping the outlet air temperature and the screen analysis in mind, until one or more of the constraints are reached.

At high production rates even a skilled operator may course severe oscillation in the screen analysis and air temperature. This is not coursed by inexperience, but because of the variety of tasks to be performed in the plant, this preventing the operator from paying full attention to the spherodizer process.

3. SYSTEM CONCEPT

3.1 The User Interface of the Fuzzy Controller

Among the system design criteria, user friendliness has been one of the most important. From the very beginning it was stressed that the system should be very easy to use both in the engineering phase (when entering new variables, rules, etc.) and in the operation phase (when controlling the process).

Therefore, a data-driven approach was chosen. This means that the user can define new variables, functions, rules, etc. just by entering data. No traditional program definitions and, thus, no program compilation is necessary. To avoid errors and inconsistencies in the data entered by the user, the system has been provided with a very comprehensive set of check-up facilities.

The user interface is based on a number of modern software technologies:

- Pop-up windows and menus
- Slot filling (fill-in the blanks)
- Options lists (pick one or several among available options)
- Mouse support (option)
- Graphics and colours

The Fuzzy Controller System can operate in 3 different modes:

- Manual Control (open loop control)
- Semi-automatic Control (The Fuzzy Controller proposes new values to the operator)
- Fully Automatic Control

If the Fuzzy Controller System is not able to control the process automatically it will immediately shift to manual control after issuing an alarm.

3.2 System Concept for the Spherodizer Process

The Fuzzy Controller is integrated in the Process Control System, like a PID-controller.

The operators allow the Process Control System to start Fuzzy control, what ever the mode of the Fuzzy Controller.

The system is based on a global database to which the Fuzzy Controller has direct access.

Signal conditioning, logical interlocking, standard PID-controllers, sequence controllers, recipes and other mathematical functions are executed in the sub-stations of the Process Control System to match the specifications for the input/output information to/from the Fuzzy Controller.

4. DEVELOPMENT AND IMPLEMENTATION OF THE ON-LINE FUZZY CONTROL SYSTEM

4.1 Project Definition

The objective of the project was to optimise the spherodizer process by implementing the logic of the "ideal" operator through a Fuzzy Controller.
At this point Kemira Denmark A/S decided to design its own system, and subsequently contracted PROCOS A/S to develop the Fuzzy Controller toolkit (or shell) and associated software to meet its requirements as a turnkey system development of a multi-variable set point Fuzzy Controller.

The total control concept of the NPK/CAN fertiliser plant is based on a PROCOS PCS-800 distributed Process Control System, where the multi-variable controller (Fuzzy) should be implemented on a stand-alone PC standard system and with RS422 communication between the Process Control System and the Fuzzy Controller.

4.2 Project Organization

As mentioned above, the main target of the project was to copy an "ideal operator" described by Fuzzy rules. The fundamental idea of the concept of the organization was to get a source of valid information on the operators' work/analyzing methods for controlling the process.

The organization concept was divided into two main activities.

- Development of Fuzzy Controller System. (System Group).
- Collection of valid information to build-up an "ideal operator". (Process Group).

The system group, which carried out the system development, had to define and accept the hardware/software performance, etc. with normal project procedure.

The process group members included: Operators, shift foremen, plant manager, chemical engineers, control engineers. The purpose of this group was to "identify" the primary variables, based on collected data from the Process Control System and operator notes on deviations from optimized production. And to determine the corresponding actions for the "ideal" operator.

4.3 Implementation

The implementation was initiated with a three-hour introduction course to the Fuzzy Controller for the plant operators. The Fuzzy Controller was started in semi-auto mode showing a superior performance already from the beginning. After a few days the controller was used chiefly in auto-mode.

The development work in the process group had a good psychological effect on the operators, who were highly motivated because of the close interaction between the various members in the process phase to the successful practical off-line test on the model, and because the operators felt responsible for the action taken by the Fuzzy Controller.

After the first couple of months it was obvious that the Fuzzy Controller was much more robust than first anticipated. Therefore, the Fuzzy Controller operation intervals, were extended to the effect that the Fuzzy Controller was now able to handle major disturbances in the process.

5. THE STRUCTURE OF THE RULE-BASED MODEL

5.1 The Program Optimisation Strategy

The process optimisation strategy in the rule-based model is based on the experience obtained by interviewing the operators. The response of the Fuzzy Controller is always consistent with the "ideal" operators reactions in the same situation, only the magnitude of the response is smaller and more frequent than the actions the operators themselves would make. The Fuzzy Controller primarily uses the following inputs

- error from set point and trend of the outlet air temperature,
- error from set point and trend of fraction of undersize in the screen analysis,

to evaluate the process situation, and to calculate the changes to the following set points on the Process Control System:

- slurry flow into spherodizer,
- air pressure on atomization nozzles,
- temperature on inlet air.

The overall philosophy of the rule-based model is: whenever the process is on its Fuzzy Controller set points, to increase the flow of the slurry into the spherodizer, and when the outlet air temperature or the fraction of undersize in the screen analysis are above their Fuzzy Controller-set points, not to reduce the inlet air temperature or the air pressure on the nozzle, but to increase the flow of the slurry. The Fuzzy Controller will follow this strategy until the process reaches its maximum, when one of the constraints in the process is reached, forcing the Fuzzy Controller to use other sets of rules, but it will still follow the same philosophy, i.e. to increase production until it reaches the practical maximum with one, two or three constraints in the process.

This reaction pattern is only valid when a NPK slurry is used. With CAN slurry the reaction of the outlet air temperature to changes in the slurry flow is reversed. It is up to the operators to choose the appropriate main program which corresponds to the recipe.

The described philosophy of the Fuzzy Controller is only carried out in the vicinity of the Fuzzy Controller set points. When the process is to far away from the set points, the purpose of the sets of rules used at this point is to return the process to the vicinity of the set points, where the philosophy described earlier takes over.

All the calculated outputs from the Fuzzy Controller are formulated as changes to the existing set points on the Process Control System. The recipe for each fertilizer grade is downloaded on the Process Control System.

The controller evaluates the rules every five minutes and writes the calculated set point changes to the Process Control System.

If, because of a major disturbance beyond the Fuzzy Controller's capacity, the process exceeds the overall definition interval for the Fuzzy Controller, the process is handed over to the operator.

5.2 Handling the Process Constraints

The program is divided into eight sub-programs corresponding to the eight different and possible combinations of constraints in the process.

A sub-program pointer is calculated in the Process Control System based on the actual constraints on the process. This sub-program pointer is sent to the Fuzzy Controller to enable the controller to recognize which sub-program to use in the actual situation.

Each of the sub-programs is duplicated - one for the situation with the process in the vicinity of the set points and one for the situation with the process to far away from the set points.

The final structure of the program, then, is one program with 16 attached sub-programs capable of handling every situation in the plant except for start-up and shut-down procedures.

5.3 The Rule Structure

The rule base comprises only a total of approx. 80 rules, but they are all expressed on a normalized basis. When the sub-programs are defined the relevant rules are picked from the list of rules. At the time when the rules in a sub-program are evaluated, and denormalized, the physical values of the rules are determined in the sub-program where they are used and not when they are defined. This is the reason for the low number of rules, although there is a extensive reuse of all the rules.

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6. OPERATING RESULTS

6.1 Production experience

In the case of a granulation process, the benefits of implementation of Fuzzy technology, are generally fairly difficult to quantify because the performance of these types of process plants are by their very nature not very consistent. In particular, the base line is constantly changing due to raw material changes and process plant modifications.

The Fuzzy Controller/Process Control System concept has reached a high level of robustness and acceptance among the operators because the Fuzzy Controller is a tool for the operator. This has made it possible to have an on-line time of the Fuzzy Controller close to 90%. The high on-line time results in a smoother and steadier control of the spherodizer, giving the following benefits

- higher production time,
- higher production capacity,
- more uniform end-product,
- less manpower.

At plant start-up it is possible for the Fuzzy Controller to take over the control of the spherodizer at 10% capacity and bring the spherodizer process to maximum production.

6.2 Case Studies

A data collection of the process variable, outlet temperature from the spherodizer (SPH) and the fraction of fines which are the main input to the Fuzzy Controller, and the output from the Fuzzy Controller are shown in figure 2.

On the curves four typical cases are shown. In case 1 it can be seen that the outlet temperature drops dramatically, perhaps due to a change in the slurry composition or a change in the spherodizer loop. When the temperature drop starts, the Fuzzy Controller begins to increase the inlet temperature and slightly decrease the increase in slurry flow. Both actions brings the outlet temperature back to set point.

In case 2 the fraction of fines increases above the set point. At this time the slurry flow is at its maximum, and consequently the Fuzzy Controller decreases the air pressure; after a while the fraction of fines decreases below the set point and the air pressure, is therefore, increased to bring the amount of fines back to set point.

When case 3 occurs, the air pressure is at its maximum, and the fraction of fines is still below set point, the only way of solving the problem is for the Fuzzy Controller to start decreasing the slurry flow.

In case 4 the plant operator decides to decrease the set point for the fraction of fines on the Process Control System. Consequently, the error from set point on the fraction of fines is changed from negative to positive. After this change of set point, the Fuzzy Controller starts increasing the slurry flow. The operator's decision to change the Fuzzy set point is based on his evaluation of the process stability. It is always up to the plant operator's own intuition (within some limits) to set the Fuzzy set points.

7. CONCLUSION

A Fuzzy Controller has been designed, by use of modern AI-technology and Fuzzy logic, with a very user-friendly interface.

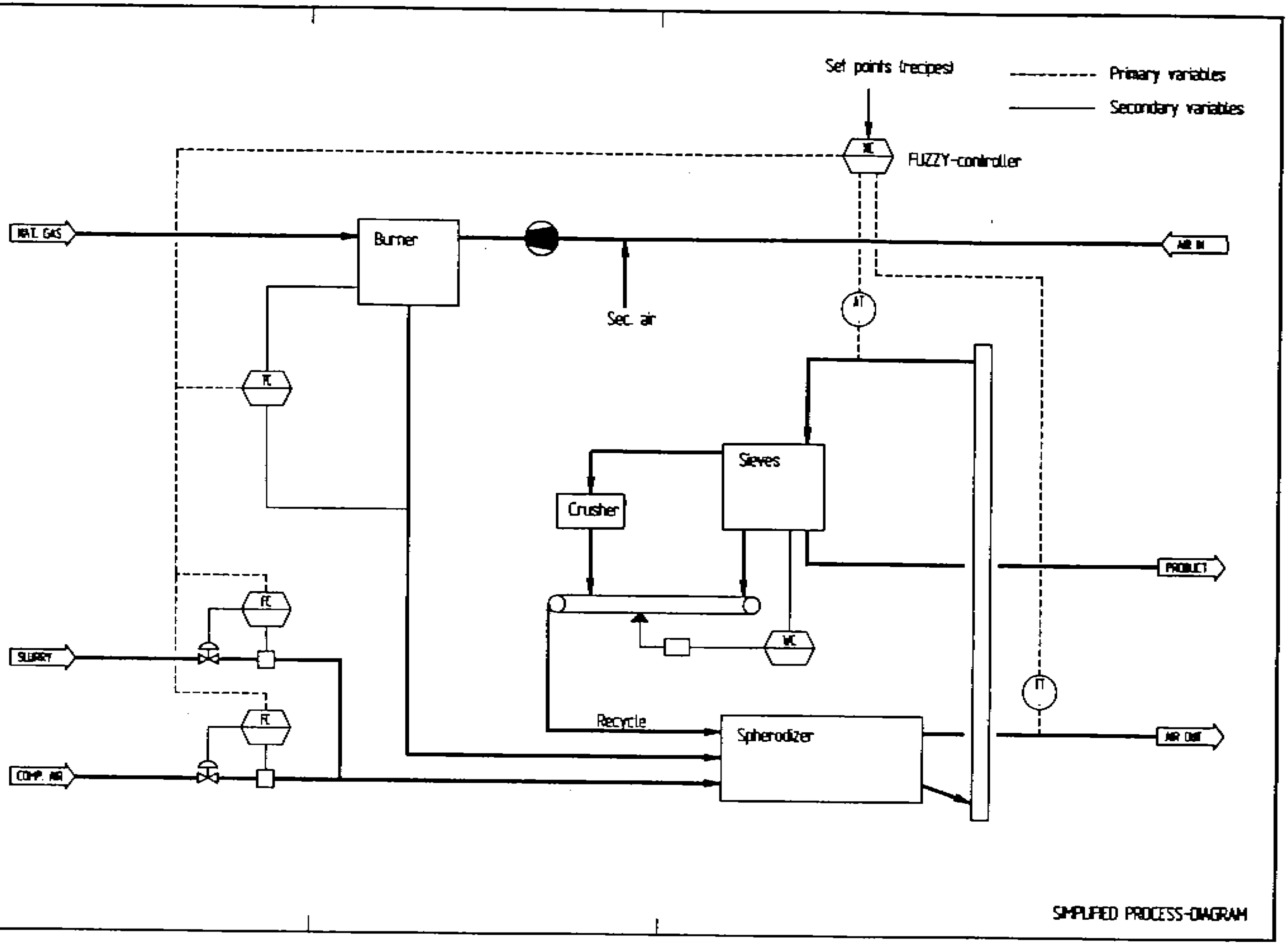
In a close interaction with plant management, plant operators, and engineers from development departments within Kemira Denmark a control strategy for the spherodizer process has been developed and implemented in a rule-based Fuzzy model.

The Fuzzy Controller receives the values from the Process Control System as errors from the primary set points, and the Fuzzy Controller sends values to the Process Control System as changes to the secondary set points. As a consequence of this, the Fuzzy Controller is independent of the currently applied set points (recipe dependent) in the Process Control System. The plant operator's only effort regarding the Fuzzy Controller is to decide which of only two possible main programs to start - the one for CAN production or the other for NPK production.

The Fuzzy Controller has been commissioned to the plant people without any organizational and justificational problems, mainly because the control strategy of the Fuzzy Controller is formulated partly by the plant operators, and they, therefore, feel responsible for the action taken by the Fuzzy Controller. The commissioning has been successful also because the Fuzzy Controller is a tool for the operator, giving him more time for other tasks.

After the Fuzzy Controller has been implemented in the process, the control of the spherodizer has become much smoother and steadier because of the frequent and optimized way in which the spherodizer now is controlled. The tighter control of the process as a whole, as well as operating the plant at optimum temperature and product quality, leads to an increased produ~~ctivity of a more uniform end-prod~~uct.

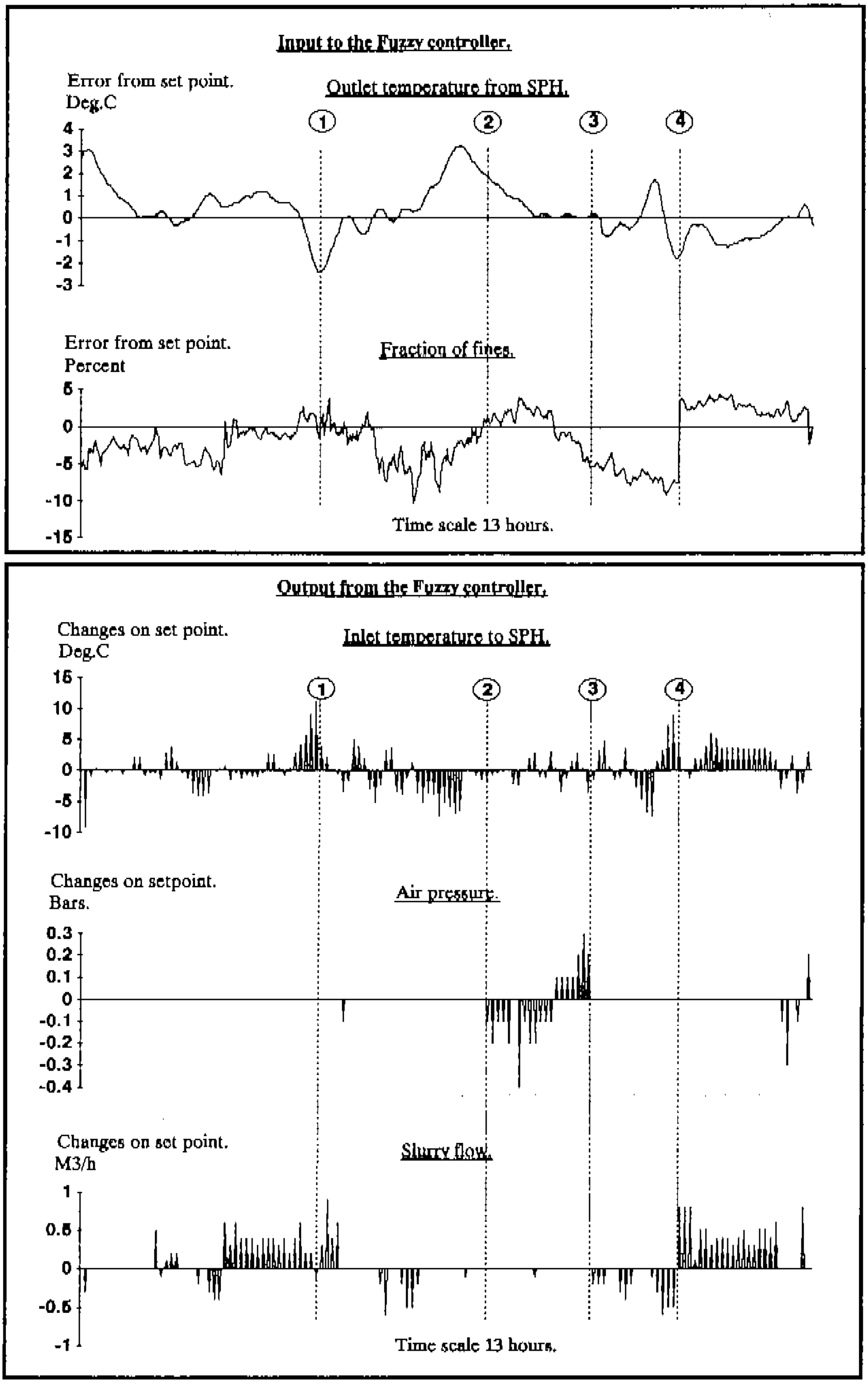
The overall result is that the process is always controlled by the "ideal" operator.



Set points (recipes)
Primary variables
Secondary variables
FUZZY-controller
Burner
Sec. air
AT
TC
Sieves
Crusher
PRODUCT
FC
WC
SLURRY
TT
Recycle
Spherodizer
AIR OUT
COMP. AIR
SIMPLIFIED PROCESS-DIAGRAM

Figure 1

Figure 2


Input to the Fuzzy controller.
Error from set point.
Deg.C
Outlet temperature from SPH.
1
2
3
4
4
3
2
1
0
-1
-2
-3
Error from set point.
Percent
Fraction of fines.
5
0
-5
-10
-15
Time scale 13 hours.
Output from the Fuzzy controller.
Changes on set point.
Deg.C
Inlet temperature to SPH.
15
10
5
0
-5
-10
1
2
3
4
Changes on setpoint.
Bars.
Air pressure.
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
Changes on set point.
M3/h
Slurry flow.
1
0.5
0
-0.5
-1
Time scale 13 hours.

APPENDIX

A. Fuzzy Theory and Principles

A.1. Introduction to the Fuzzy Theory

Some industrial processes are very difficult to control with a conventional Process Control System (PID-controllers). This includes slow, non-lineary processes with large (and varying) time lags. Most of these processes can often be controlled in a satisfactorily way by an operator from heuristic rules:

"If the temperature is too low and does not rise, then open the steam valve a little more."

The concepts "too low" and a "little more" are interpreted very differently by different operators, so the control of the process is not uniform. The idea with a Fuzzy Controller is to operate as an "Ideal Operator" according to similar rules, but in an uniform and optimized way.

The word "Fuzzy" means "not clear" or "loose", and from the above heuristic rule the reason is obvious. An example: Set point is 60 deg.C and temperature is 58 deg.C. Of course the temperature is below the set point, but is the temperature then "too low"? And what if the temperature is 15 deg.C? The concept "too low" is a loose term, and it is obvious that the temperature is more "too low" when the temperature is 15 deg.C compared to 58 deg.C.

A Fuzzy Controller is a functional "black box", like a PID-controller, but unlike the PID-controller it is not a mathematical model with an unambiguous connection from input to output. It is a "rule base" with many loose formulated rules, a so-called "Knowledge Base". Therefore, Fuzzy control is a way to make a precise operation with unprecise data.

A.2. Fuzzy Control Rules

As mentioned earlier, Fuzzy rules are of the following form:

IF <conditions> THEN <action>

For example we can have the following three rules:

IF temp IS low THEN valve IS small-positive (Rule 1)
IF temp IS ok THEN valve IS zero (Rule 2)
IF temp IS high THEN valve IS small-negative (Rule 3)

where "temp" and "valve" are called "Linguistic Variables" and "low", "ok", "high", "small-positive", "zero" and "small-negative" are called "Fuzzy Variables".

Process variables are often normalized to a range from -1 to +1 from the normal working range (see figure A.1).

"Fuzzy Variables" are described by "General Membership Functions" to specify how "true" the conditions are. Figure A.2 shows the general membership functions for "low", "ok" and "high". Further, it shows that a temperature at 35 deg.C is, in this case, 40% true in being "low", 80% true in being "ok" and 1% true in being "high". From this example we can also see that the rules may contradict each other: The temperature can be "low", "ok" and "high" at the same time (but not to the same extent).

Figure A.3 shows the general membership functions for the Fuzzy Variables "small-negative", "zero" and "small-positive".

A.3. How does the Fuzzy Controller Operate?

The Fuzzy Controller operates in five steps:

1. First it reads the input variable(s) - in this case the temperature.

2. Then the input variable(s) is normalized to a value between -1 and +1. Figure 4.1 shows that the normal operating range is from 10 deg.C to 90 deg.C in our example.

3. The third step is to evaluate the control rule(s) and deduce the output value(s). This will be explained further in the following section.

4. Then the output value(s) is de-normalized to a "physical" value. In this case the range from -1 to +1 is denormalized to a valve value from 0-100% open.

5. The final step is then to write the de-normalized output value(s) to the process.

A.4. Evaluation of Control Rules and Deduction of Output Values

To understand how the evaluation of control rules and deduction of output values are done, we will look at a concrete example.

All the control rules are evaluated in turn.

Figure A.4 shows how rule 1 "IF temp IS low THEN valve IS small-positive" is evaluated.

The normalized value of "temp" is looked-up in the general membership function for "low". This gives a value of 40%. Then the general membership function for "small-positive" is scaled with 40%, as shown in the above figure.

Evaluation for rules 2 and 3 is done in exactly the same way. Figures A.5 and A.6 show the evaluations.

When all the rules have been evaluated, the Fuzzy Controller only has to deduce the output value. This is done by super-imposing all scaled general membership functions for the output variable(s) - in this case "valve". See figure A.7. Now the "centre of gravity" is found by numerical integration. (The "centre of gravity" is the normalized output value, where 50% of the area of the super-imposed curve is to the left and 50% to the right). In our example we can see that the centre of gravity is at 0.22 corresponding to a 61% opening of the valve.

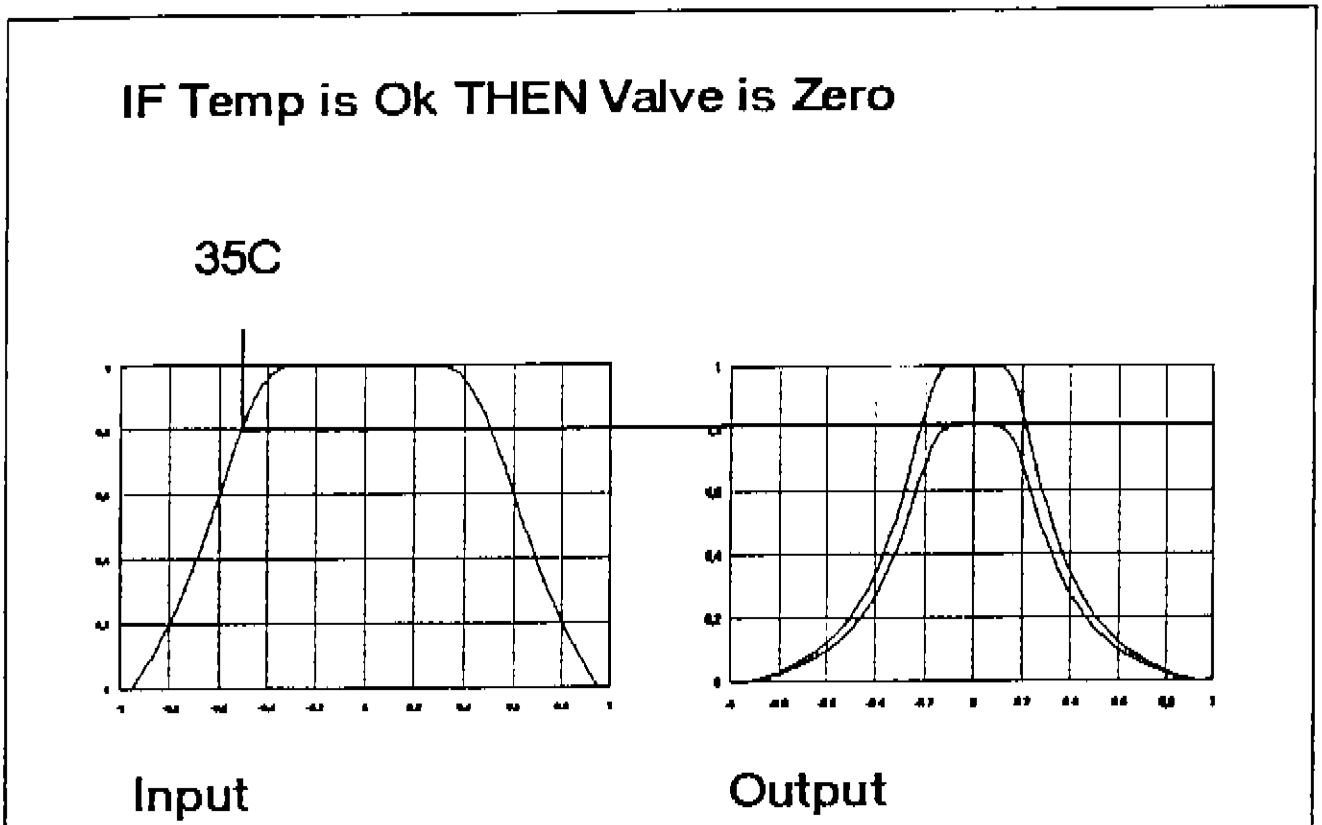


Figure A.5

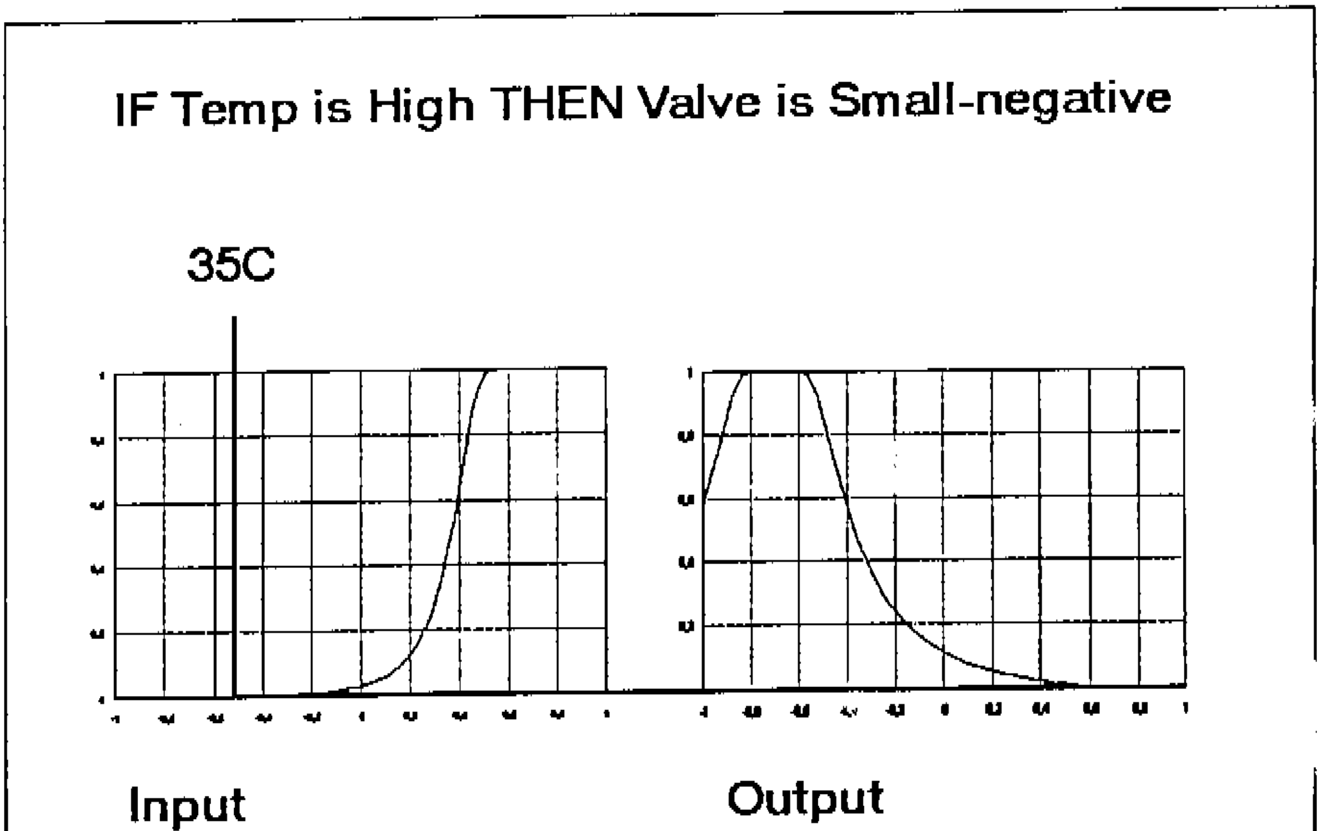


Figure A.6

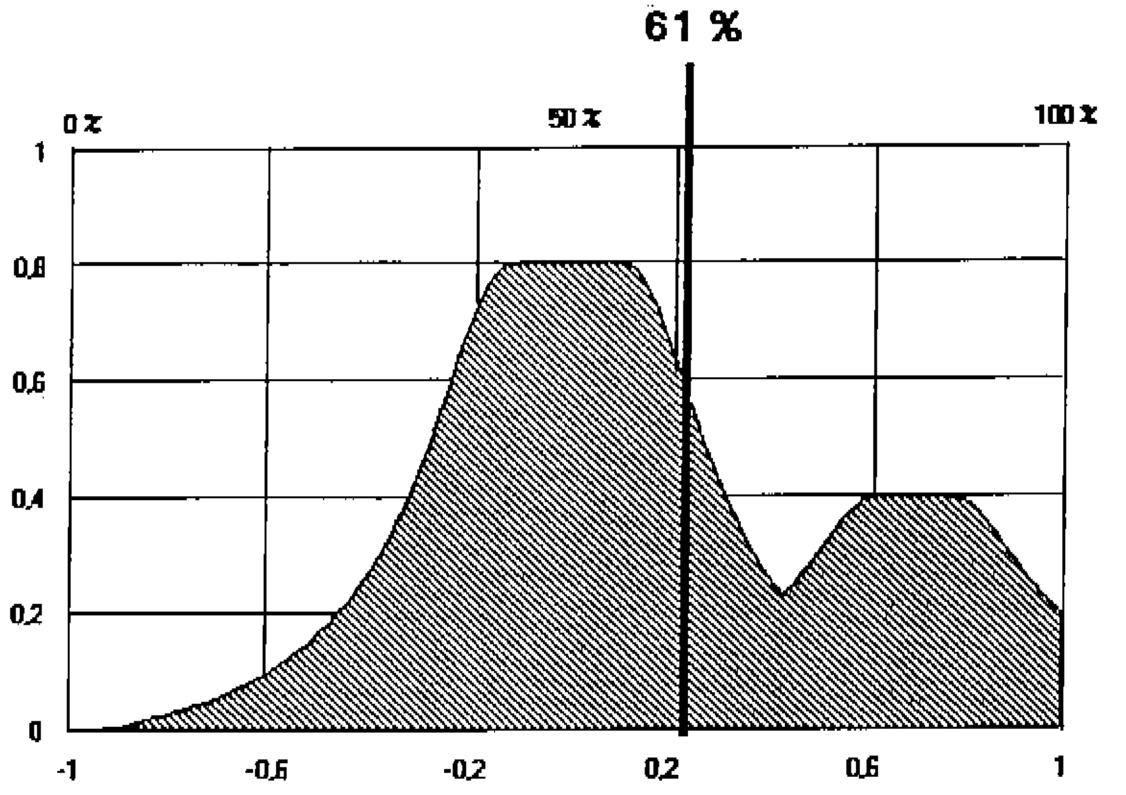


Figure A.7