# Fuzzy Logic Modeling of the Fluidized Catalytic Cracking Unit of a Petrochemical Refinery

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## ABSTRACT

This paper describes investigations carried out regarding the application of Fuzzy Logic Control to the Fluidized Catalytic Cracking Unit (FCCU) of Kaduna Refinery and Petrochemical Company in Northern Nigeria, as a case study. An optimal control solution where the objective is to determine a well-defined relationship between the vital variables (reactor temperature/riser outlet temperature, regenerator gas temperature, regenerated catalyst feed rate, and the airflow rate) through the use of Fuzzy Logic control scheme is the focus of this paper.

In the catalytic cracking unit, feed oil is contacted with re-circulating catalyst and reacted in a riser tube. The feed oil vaporizes and is cracked as it flows up the riser, thus forming lighter hydrocarbons (the gasoline fraction). Large amounts of coke are formed as a by-product. The coke deposits on the catalyst and reduces its activity. The lighter hydrocarbon products are separated from the spent catalyst in the 'reactor'. Steam is supplied to strip volatile hydrocarbons from the catalyst. The catalyst is then returned to the regenerator, where the coke is burnt off in contact with air. This is usually done by partial or complete combustion. The regenerated catalyst is then re-circulated back to mix with the inlet feed oil from the crude unit. [1].

The behaviour of the reactor temperature/riser outlet temperature and the regenerator gas temperature during the chemical reactions in the FCCU were simulated using MATLAB®. The problem of control, will however involve the control of two outputs (reactor temperature/riser outlet temperature and the regenerator gas temperature) by manipulating the two inputs (regenerated catalyst feed rate and the airflow rate), which are the critical and vital factors for optimization of the cracking process in the FCCU. A relationship was developed between the above stated input(s) and output(s) with the help of the fuzzy logic controller. This will facilitate optimization of gasoline production.

(Keywords: process engineering, control models, fuzzy logic, hydrocarbon, gasoline production, industrial catalyst)

## INTRODUCTION

Optimization of gasoline production poses a big challenge in the petrochemical refinery because the input and output variables are non-linear, interdependent, and full of uncertainties. The problem for this study is to develop a controller (using Fuzzy Logic) to model the response of the FCCU to regenerated catalyst feed rate and airflow rate. The modeled information is in turn used to design a control solution to read the reactor temperature/riser outlet temperature and the regenerator gas temperature of a FCCU, and adjust the regenerated catalyst feed rate and air flow rate accordingly for optimal performance.

Giving the non-linear and interdependent nature of input and output in the FCCU, the simple false or true logic cannot adequately deal with the ensuing control situation.

Fuzzy Logic is a systematic mathematical formulation for investigating and characterizing different types of uncertainties. It is best suited when a mathematical model of the process does not exist; exists but is too complex to be evaluated fast enough for real time operation; or is too difficult to encode. In such situations, difficulties arise in using traditional control methods [12].

Due to the lack of a precise mathematical model for the process being controlled, rule based fuzzy control may be adequate because no exact and explicit process models are required.

One such suitable candidate for fuzzy control is the process of upgrading heavy hydrocarbons to lighter more valuable products by cracking, in the FCCU of a petrochemical refinery.

Catalytic cracking is a refinery process that seeks to increase the gasoline and liquefied petroleum gas (LPG) production, through the heavy vacuum gas oil and residue conversion in lighter fractions. Because of its impact on overall refinery economics, the FCCU is the best unit to apply advanced control and optimization strategies, and the base for these is always a good mathematical model. The model has to be able to reproduce reasonably well the main dynamics and stationary gains of the system, without compromising the computational load.

There are many mathematical models for the FCC in the literature. Some of these use a simplified cracking process description, and a few of them present integration between regenerator and riser. Most are based on model with a high degree of empiricism, and make use of pseudo-components corresponding to different groups of species, usually called lumps [6].

Among the cracking kinetic models, there is the 3 lumps model of [18], a 10 lumps model by [7], and more recently [15] developed a model with 19 lumps, approximating the reactants and products according to the crude oil cuts composition. Among the integrated models, [13] published a well-detailed model based on the obsolete Exxon Model IV with a realistic description of the regenerator fluid-dynamic behaviour; however the combustion reactions were not considered. It also lacks a detailed description from cracking kinetics, making the riser useless for dynamic or stationary control.

More recently [1] developed a model that provides a detailed description of the combustion and cracking kinetics, using the 10 lumps model of [7] to represent the mixture in the riser.

As already pointed out by [4], an important limitation in most of these models is the fact that they ignore the complex two-phase nature of the fluidized beds in the regenerator. The objective of this work is to present a fuzzy logic approach based on actual plant data.

To optimize the cracking process in the FCCU, a Fuzzy Logic controller has been designed in this research work, so as to get a well-defined relationship between the manipulated input and the output variables by use of a Fuzzy Model. The Fuzzy Logic controller has been simulated on a digital computer using MATLAB® 5.0 Fuzzy Logic Tool Box.

## THE FLUIDIZED CATALYTIC CRACKING UNIT – A BRIEF DESCRIPTION

Fluidized catalytic cracking (FCC) is an important process in oil refineries. It upgrades heavy hydrocarbons to lighter more valuable products by cracking, and is the major producer of gasoline in refineries. FCCUs present challenging multivariable control problems. The selection of good inputs (manipulated variables) and outputs (measured variables) is an important issue, as is the pairing of chosen controlled and manipulated variables for decentralized control. A simplified process schematic and instrumentation diagram is shown in the figure below. [11].

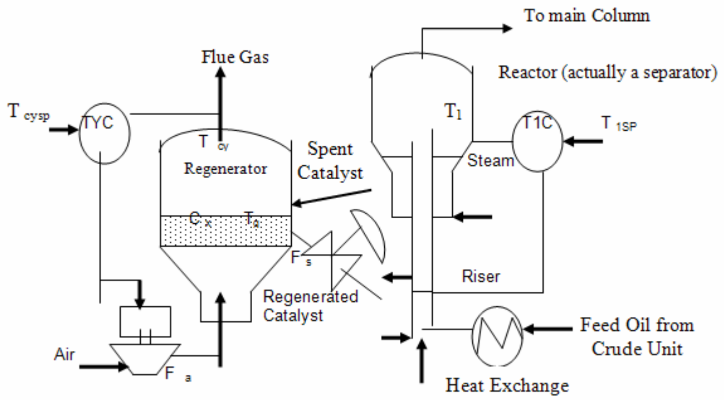

**Figure 1:** Schematic Diagram of FCCU [19].

The heavy molecule cracking process occurs in a riser tubular reactor, at high temperatures, building up fuel gas, LPG, cracked naphtha (gasoline), light cycle oil, decanted oil, and coke. The coke deposits on the spent catalyst surface causing its deactivation. The catalytic activity is re-established by coke combustion in a fluidized bed reactor, dominated regenerator.

The system riser-regenerator is called the converter. Steam lifts the heated regenerated catalyst to be combined with the oil in the riser so that the oil-catalyst mixture rises in an ascending dispersed stream to the separator. The control valve manipulates the quantity of hot regenerated catalyst from the standpipe to the riser in order to maintain a predetermined outlet riser temperature. On the top of the separator, the catalyst particles are separated from vapor products by cyclones. The stream transfers the reaction products overhead to the products recovery section. The standpipe transfers spent catalyst continuously from the separator to the regenerator by a control valve.

In the regenerator, spent catalyst particles are burned in the presence of air. The air flow rate to the regenerator is controlled by a control valve that vents portions of the air to the atmosphere. On the top of the regenerator, cyclones perform the catalyst separation from the flue gas stream [10].

A control valve regulates flue gas flow in order to vary the internal regenerator pressure maintaining the desired pressure difference between separator and regenerator. The flue gas goes to a carbon monoxide boiler where carbon monoxide is converted to carbon dioxide. There is a recycle stream around the wet gas compressor to control the suction pressure, which maintains the converter pressure at its desired value.

The measured variables are riser temperature, regenerator temperatures, wet gas compressor suction pressure, separator-stripper catalyst level, separator-regenerator differential pressure and regenerator flue gas temperature. The manipulated variables are feed flow rate, preheated feed temperature, catalyst circulation rates, combustion air flow rate and wet gas compressor recycle rate. The measured disturbances are feed characteristics, feed temperature, and air temperature [2].

## FUZZY CONTROLLER DESIGN FOR FCCU

As mentioned earlier, during cracking, feed oil vaporizes and is cracked as it flows up the riser, thus forming lighter hydrocarbons. This leads to the formation of large amounts of coke, which deposits on the catalyst and reduces its activity. Given the complexity of the entire process, traditional system modeling for control design (involving the derivation of a mathematical model to describe the system) that in turn requires deep understanding of all variable involved is too difficult. Hence, Fuzzy Modeling, which deals with the relationship of the output to the input, considering many other parameters is employed.

In the design of a Fuzzy Logic Controller, system adjustments are handled by a Fuzzy Rule-Based Expert System [17] [3]. We'll adopt the knowledge base approach, which consists of the following components (Figure 2):

(a) **Data Base** - that contains knowledge used to characterize Fuzzy Control Rules and Fuzzy Data Manipulation in an FLC, which are defined based on experience and engineering judgment of an expert. In this case, an appropriate choice of the membership functions of a fuzzy set plays a crucial role in the success of an application.

(b) **Rule Base -** that is characterized by construction of a set of linguistic rules based on experts' knowledge. The expert knowledge is usually in the form cause and effect i.e. IF – THEN. Fuzzy statements can thus easily implement this.

### Controller Design

We define (5) linguistic values for the fuzzy system as follows:

| | |
|---|---|
| "1" = Negative Big (NB) | 'Very Low Consequent' |
| "2" = Negative Small (NS) | 'Low Consequent' |
| "3" = Steady State (SS) | 'Steady State' |
| "4" = Positive Small (PS) | 'High Consequent' |
| "5" = Positive Big (PB) | 'Excessive High Consequent' |

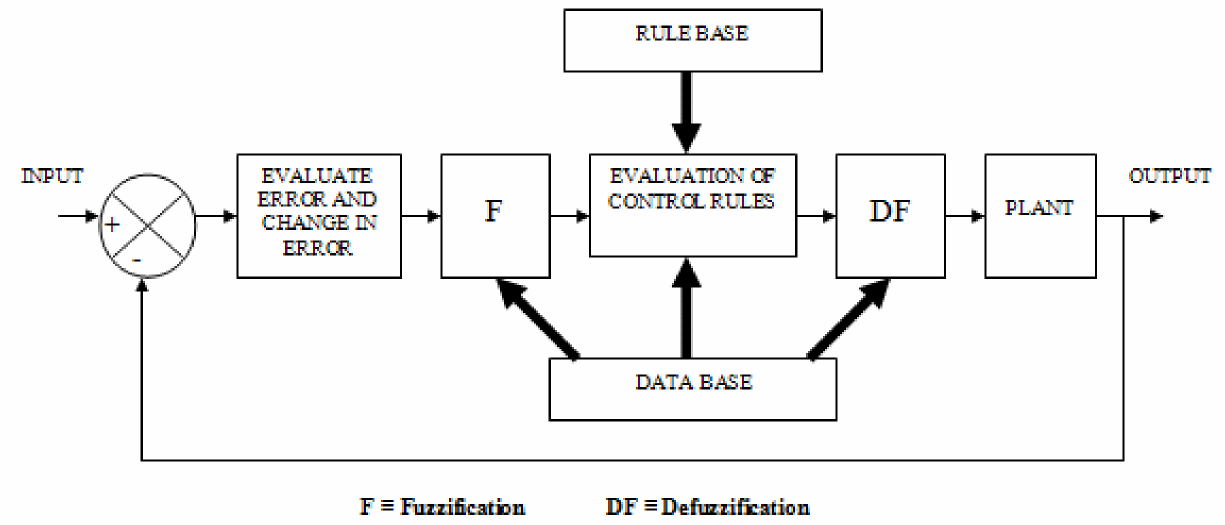

**Figure 2:** General Structure of a Fuzzy Feedback Control System.

This rule base is derived based on the following assumptions.

1. The SISO process has a monotonic input – output relationship, not a necessarily linear relationship.
2. The control goal is to maintain a controlled variable at a desired level by manipulating process input.
3. The response of the system will not be ideal, due to the inertia property possessed by the process.

## Rule Base

Using derivation based on expert experience and control engineering knowledge; the experience of an operator who has been working at the Kaduna Refinery and Petrochemical Company located in Northern Nigeria for over 12 years was used to obtain the rule base. The operator is also our expert in defining the fuzzy rules and the fuzzy set.

**Table 1:** Fuzzy Rules for Airflow Rate.

| Riser Outlet Temp →<br>Reactor Cyclone Temp ↓ | **PB** | **PS** | **SS** | **NS** | **NB** |
|---|---|---|---|---|---|
| **PB** | 5 | 4 | 3 | 1 | 1 |
| **PS** | 5 | 4 | 3 | 1 | 1 |
| **SS** | 5 | 4 | 3 | 2 | 1 |
| **NS** | 5 | 4 | 4 | 3 | 1 |
| **NB** | 5 | 5 | 5 | 4 | 3 |

“1” = Negative Big, “2” = Negative Small, “3” = Steady State, “4” = Positive Small, “5” = Positive Big

**Table 2:** Fuzzy Rules for Catalyst Feed Rate.

| Riser Outlet Temp →<br>Reactor Cyclone Temp ↓ | **PB** | **PS** | **SS** | **NS** | **NB** |
|---|---|---|---|---|---|
| **PB** | 5 | 5 | 3 | 1 | 1 |
| **PS** | 5 | 4 | 3 | 1 | 1 |
| **SS** | 5 | 4 | 3 | 2 | 1 |
| **NS** | 3 | 3 | 2 | 2 | 2 |
| **NB** | 3 | 3 | 2 | 1 | 1 |

“1” = Negative Big, “2” = Negative Small, “3” = Steady State, “4” = Positive Small, “5” = Positive Big

**Table 3:** Fuzzy Rules for Oil Feed Rate.

| Riser Outlet Temp →<br>Reactor Cyclone Temp ↓ | **PB** | **PS** | **SS** | **NS** | **NB** |
|---|---|---|---|---|---|
| **PB** | 5 | 5 | 5 | 2 | 1 |
| **PS** | 5 | 4 | 4 | 2 | 2 |
| **SS** | 5 | 2 | 3 | 2 | 1 |
| **NS** | 3 | 1 | 2 | 1 | 1 |
| **NB** | 2 | 1 | 1 | 1 | 1 |

“1” = Negative Big, “2” = Negative Small, “3” = Steady State, “4” = Positive Small, “5” = Positive Big

## Case Study Descriptions

The FCCU at Kaduna Refinery and Petrochemical Company in Northern Nigeria was the case study used for this research paper.

## Fuzzy Sets Formation

The membership function plots for the catalyst feed rate, airflow rate, feed oil rate, regenerated cyclone temperature, riser outlet temperature and the regenerator bed temperature are as shown below. These form the main parameters in the cracking system in an FCCU. We employed these datasets in the design of the rule base for the Fuzzy Logic Controller.

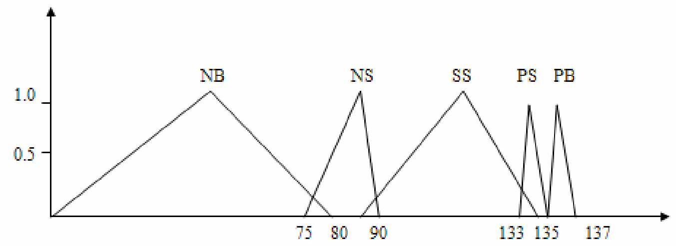

**Figure 3:** Membership Function for Catalyst Feed Rate (tons/day).

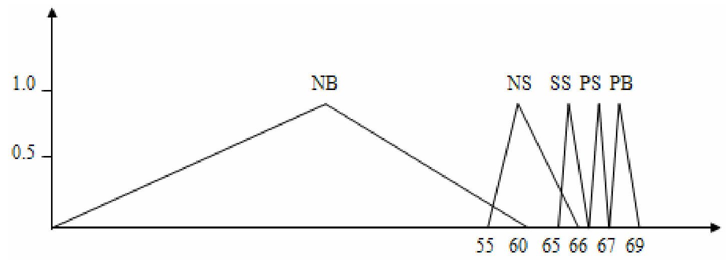

**Figure 4:** Membership Function for Airflow Rate (Kg/sec).

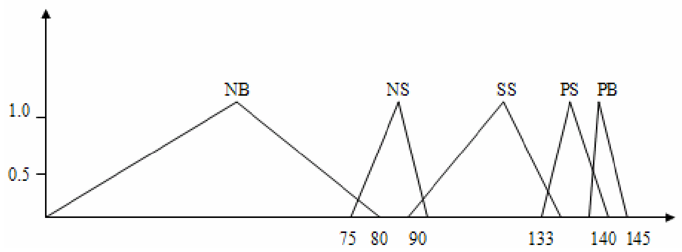

**Figure 5:** Membership Function for Oil Feed Rate ($m^3$/hr).

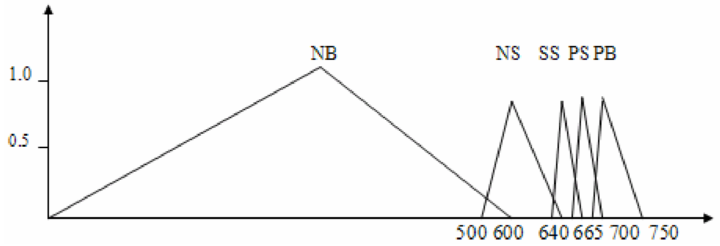

**Figure 6:** Membership Function for the Regenerator Cyclone Temperature (C).

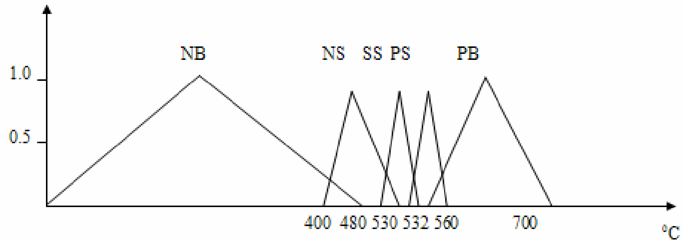

**Figure 7:** Membership Function for the Riser Outlet Temperature (C).

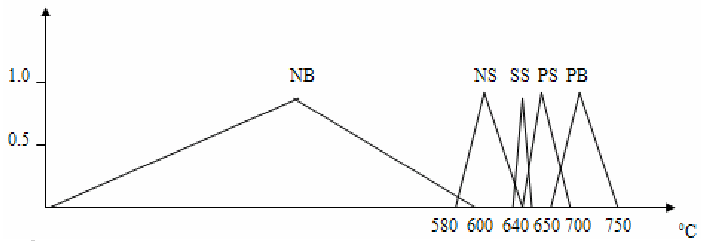

**Figure 8:** Membership Function for the Regenerator Bed Temperature (C).

The Fuzzy Superior Controller was simulated using MATLAB® 5.0 Fuzzy Logic Toolbox. Our goal was to establish a functional relationship between the input variables, which are the regenerated catalyst feed rate and the airflow rate, and the output variables (i.e. riser outlet temperature and regenerator cyclone temperature). The variables in consideration are regarded as the most important with respect to hydrocarbon cracking, energy consumption, and product quantity.

The objectives set for the cracking process in the FCCU are to:

- Maximize unit capacity
- Maintain product quality while maximizing yields of most valuable products
- Optimize energy utilization
- Control conversion
- Improve safety and reliability via operational stability

It has been found that the set objectives depend on the catalyst flow by minimizing catalyst attrition and increasing fines retention. Irrespective of the catalyst type, density, and particle size distribution, this improves:

- stripping efficiency
- regeneration capability
- the range of catalyst circulation rates
- pressure profile
- riser temperature control

These improvements are essential to subsequent improvements in:

- unit conversion
- product selectivity
- catalyst stability in the presence of contaminants

And, they minimize:

- coke and gas production
- catalyst consumption and air pollution

This results in a more stable and flexible operation that is easier to operate close to unit constraints and achieve substantial gains in unit performance.

## RESULTS

Figures 9, 10, 11, and 12 represent the graphical form of results obtained through this study. They are the typical curves of:

i. The catalyst feed rate as a function of the regenerator cyclone temperature (Figure 9).

ii. The catalyst feed rate as a function of the riser outlet temperature (Figure 12).

Figures 9, 10, 11, and 12 show the input and the output after modification and enhancement by tuning. To achieve this level of enhancement, the rules and the centers of the input and output membership functions were changed.

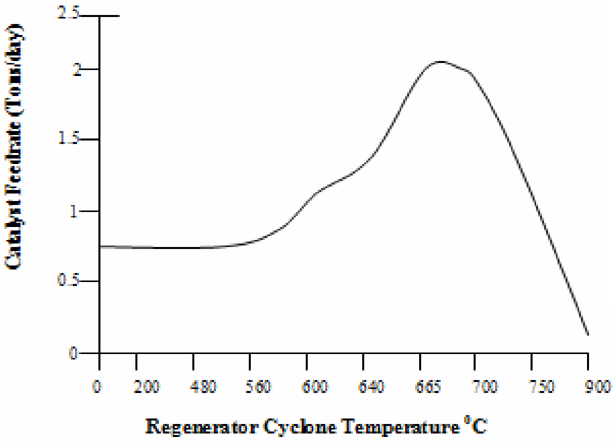

**Figure 9:** Catalyst Feed Rate as a Function of the Regenerator Cyclone Temperature.

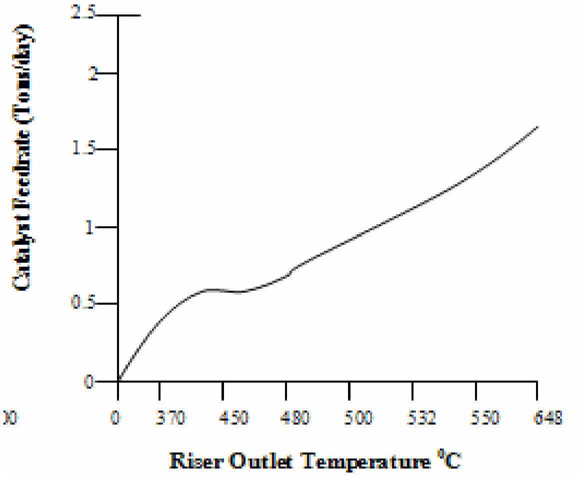

**Figure 10:** Catalyst Feed Rate as a Function of the Riser Outlet Temperature.

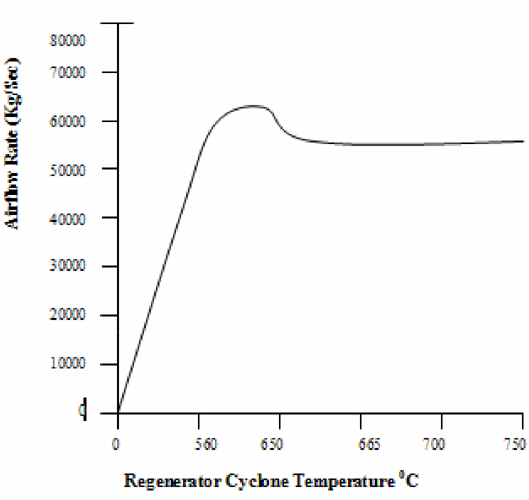

**Figure 11:** Airflow Rate as a Function of the Regenerator Cyclone Temperature.

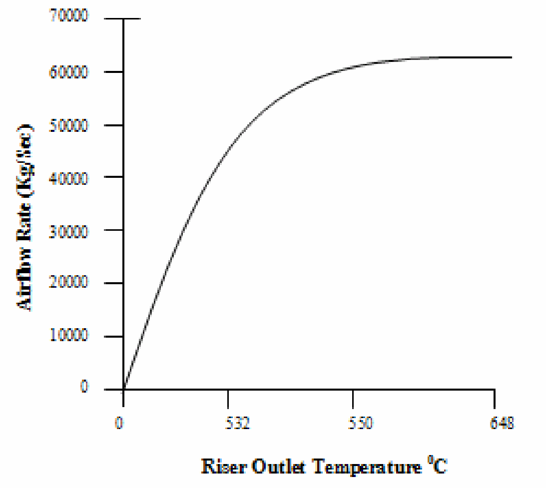

**Figure 12:** Airflow Rate as a Function of Riser Output Temperature.

Figure 9 shows that the catalyst feed rate was almost constant for regenerator cyclone temperatures below 560 C. For temperatures ranging from 580 C to 680 C, the regenerator catalyst feed rate rises steadily. The catalyst feed rate reaches a peak at 680 C and a sharp decline is seen for temperatures greater than 700 C.

These means that an increase in the input variable (i.e. the regenerator cyclone temperature) leads to a significant change in the catalyst feed rate. The range of catalyst circulation rates (1.0 tons/day to 2.0 tons/day) and catalyst stability in the presence of contaminants is greatly impacted by regenerator cyclone temperature. In order to minimize catalyst attrition and increase fines retention, the regenerator cyclone temperature should be kept as long as possible between the 645 C and 680 C range. Once the temperature reaches that stage, the relationship represents that of a piecewise linear system, expressed mathematically as:

$x_0\ (t) = b_0 x_0(t);$

$b_0$ positive or negative:
$x_i$ (t) = input;
$x_0$ (t) = output

Figure 10 shows that the catalyst feed rate rises steadily as riser outlet temperature increases. A peak catalyst feed rate of about 1.7 tons/day is obtained at a temperature of 648 C.

This implies that optimizing energy utilization by riser temperature control improves unit conversion. The riser outlet temperature, if sustained at a high temperature (greater than 500 C), will lead to a catalyst feed rate of about 1.0 tons/day to 1.7 tons/day, a range within which the regenerator cyclone temperature is also plausible as seen in Figure 9. This is a linear relationship that can be expressed mathematically as:

$x_0(t) = b_0 x_i\ (t)$

Figure 11 shows that the airflow rate rises steadily to $62 \times 10^3$ kg/sec until the regenerator cyclone temperature gets to 600 C, and remains steady at this temperature until it reaches 650 C. There is a sharp decline in the airflow rate between temperature 650 C and 657 C of the regenerator cyclone. The airflow rate then remains at this level until the regenerator cyclone temperature of 750 C is reached. This means that an increase in the input variable i.e. the regenerator cyclone temperature does not bring a significant change in the airflow rate. Air flow distribution remains constant immediately after the regenerator cyclone temperature reaches 657 C. In order to save energy consumption, the regenerator cyclone temperature can be kept constant at 657 C. The relationship obtained represents a second order system, expressed mathematically as:

$$a_2 \frac{d^2 x_0}{dt^2} + a_1 \frac{d x_0}{dt} + a_0 x_0 = b_0 x_i (t)$$

Figure 12 shows that the riser outlet temperature, if sustained at 550 C, would lead to savings in energy consumption and minimize coke and gas production. Riser outlet temperatures greater than 550 C do not provide any incremental addition to the airflow rate. The input variable should therefore be kept at a steady state of 550 C as soon as the temperature is reached. The relationship obtained represents that of a second order system, expressed mathematically as:

$$a_2 \frac{d^2 x_0}{dt^2} + a_1 \frac{d x_0}{dt} + a_0 x_0 = b_0 x_i (t)$$

$x_i$ (t) = input;
$x_0$ (t) = output

From the results of the simulation, we have been able to establish a relationship in the form of graphs for the following:

a. Catalyst feed rate as a function of Regenerator cyclone temperature and riser outlet temperature (Figures 9 and 10).

b. Airflow rate as a function of Regenerator cyclone temperature and riser outlet temperature (Figures 11 and 12).

We have been able to establish concrete relationships between the input and output variables that are required to optimize the FCCU products by enhancing the cracking process. By application of a suitable numerical analysis method to these results, a more linear relationship may be obtained.

## CONCLUSION

The Fuzzy Model that was designed and described in this paper is capable of managing the characteristic uncertainties and imprecision normally associated with the catalytic cracking process in an FCCU. The controller has proved to be capable of providing a workable Fuzzy Model, taking into account the objective of the optimization problems associated with the process.

When compared with other methods such as model predictive control, etc. this research has demonstrated and established the advantage of relative ease of design and implementation of control systems offered by Fuzzy Logic.

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## SUGGESTED CITATION

Osofisan, P.B. and O.J. Obafaiye. 2007. “Fuzzy Logic Modeling of the Fluidized Catalytic Cracking Unit of a Petrochemical Refinery”. *Pacific Journal of Science and Technology*. 8(1):59-67.

Pacific Journal of Science and Technology