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# Application of sensitivity analysis to oil refinery emissions

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**Abstract**

Catalyst emissions from fluidising catalytic cracking units have the potential to impact significantly on the environmental compliance of oil refineries. Traditionally it has been assumed that gas velocity and fine particles significantly impact on emission levels. Through the use of a simple fluidised bed model, sensitivity analysis was conducted to identify the key operating parameters that influence emission rates. It was found that in addition to velocity, density and mid sized particles are the most influential factors for emission rates. Further work is needed to identify how these parameters can be altered during normal operations to reduce catalyst emissions.


*Keywords:* Modelling; Sensitivity analysis; Fluidising catalytic cracking units; Air pollution

## 1. Introduction

The petroleum industry currently employs fluidising catalytic cracking units (FCCUs) as the major tool in producing gasoline from crude oil (Fig. 1). FCCUs typically consist of a rising main where the chemical reactions between catalyst and hydrocarbons occur, a reactor to separate the product and catalyst, and a regenerator to recharge the used catalyst. The regenerator is a fluidised bed used to combust coke from the used catalyst, with cyclones to remove particles from the flue gas stream before venting to the atmosphere. The recharged catalyst then recirculates through the rising main and the process is repeated [1].

In recent years, fine particle emissions from industry have been identified as important contributors to poor environmental and health standards across the United States [2]. With increasing demands for cleaner air, catalyst emissions from FCCUs have the potential to impact significantly on the environmental efficiency of the overall refining operation [3]. Currently, FCCUs are designed and operated in such a way as to maximise output and profitability of the refinery, while using end of pipe control technology to clean emission gas before they reach the atmosphere [4,5]. Thus there is a need for the relationships between current operational strategies and air pollution to be better understood allowing cheaper operational changes to be used to modify emission levels.

The aims of this paper are twofold, firstly to identify the key operating parameters in terms of catalyst emissions from FCCUs, and secondly, to provide the foundation to develop a more detailed FCCU emission model to confirm the sensitivity results.

## 2. Background

Matlab was used to develop a model to predict catalyst emissions from the fluidised bed, through the use of operating parameters of the system. The objective of the model was to produce qualitative trends of emissions, rather than a tool for representative estimates.

### *2.1. Model background*

Fluidisation is an extremely large area of research, in which a wide number of different approximations and models are used to predict all aspects of the system. However, fluidisation is still to a large extent which is not fully understood [6]. The complexity and accuracy of each model is dependent on the conditions and underlying assumptions used to develop and construct each model. To overcome this, a detailed literature review was completed to identify the key areas important to fluidisation. From here a simple model was developed to link a large number of individual equations, dealing with such phenomena as entrainment, elutriation, cyclone efficiency, and bed

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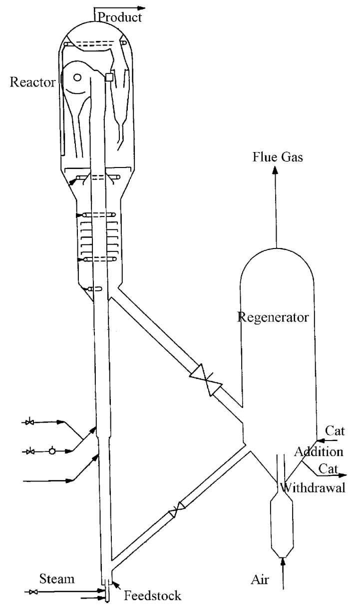


Fig. 1. FCCU stylised schematic.

effects, in order to develop a basic emission model for a FCCU fluidised bed. Worked examples from the literature were used to validate the model and test the accuracy of the output. Once the model was operating correctly, real life FCCU operating conditions were used to track emission trends. Thus, the aim of the model was to track final air emission trends from a typical FCCU in kg/s. The sequential set up of the model allowed the user to investigate the physical considerations that relate to total emission rates at any stage of the FCCU process. These model steps, outlined later, are not dealt with directly in the sensitivity analysis, but are included in this paper as they provide a more detailed understanding of the model process and add value to the sensitivity results.

The model is a function of the form of $y = f(x)$, where $x$ is a matrix of 12 input elements and $y$ the emission level in kg/s of particle solids. The solution, $y$ is found, and the sensitivity of $y$ to the 12 input variables is determined. The model, using the initial operating parameters, steps through a series of sub-routines, each comprising one non-linear equation, to calculate a specific process in the fluidised bed (25 specific processes in total). As independent equations, each sub-routine uses a combination of operating parameters and/or the solution to a previous sub-routine to calculate a solution. Thus, the sub-routines are coupled to enable the exchange of data in such a way that the output of one sub-routine will become the input of another. The model steps through the fluidising process, from start to finish until the final emission rates are determined. During this process, data is collected to allow corrections and calibrations to be made.

Currently there is no feed back loop to account for catalyst material returned to the FCCU from the cyclones or attrition processes. This limits the accuracy of the model for prediction purposes, as a feedback loop will alter the particle composition, thus altering the results of all other processes. Without a feedback loop the model deals with a simplified bed composition and cannot determine emission rates in real life situations where the bed composition fluctuates over time. As the objective of the modelling exercise is to determine the sensitivity of air emissions to input parameters, the removal of the feedback loop simplifies the calculations without altering the way the actual system operates. Thus the modelling is a preliminary analysis of a FCCU and its operation.

### 2.2. Sensitivity analysis

Sensitivity analysis was selected as the technique to be used to determine which operating parameters influenced emissions from FCCUs. The model used for the refinery, is relatively simple in that it deals only with steady state conditions. It is incomplete in that dynamic, i.e. effects in time are not considered. Inclusion of such effects leads to a much more computationally demanding model. Given the preliminary nature of this model, a 'one-factor-at-a-time' (OAT) screening method was selected as the preferred sensitivity analysis technique. The use of an OAT method for this initial test, also allows future, more computationally demanding models to be tested and results compared using the same standard sensitivity method. The Morris method is one such OAT method which provides sensitivity estimates of total effects and an overall sensitivity measure of curvature and interactions between factors [7].

To understand further about the interactions inside the FCCU and how these interactions influence catalyst emissions, a higher order sensitivity analysis was also used on the model. The New Morris method, as developed by Campolongo and Braddock [7], was selected and used to test for second order interactions in the model's input parameters for sensitivity. The New Morris method [7] is an extension of the original Morris method extended to identify second order interactions between input parameters. In doing so these New Morris methods provide an estimate of the output sensitivity for any pair of input parameters, while minimising the computational cost of the evaluation [7]. The sensitivity analysis was conducted on the entire model and not specific sub-routines. The 12 input variables (Table 1) were used to generate emission levels and sensitivity results for the complete model.

The software developed by Campolongo and Braddock [7], and corrected by Cropp and Braddock [8] allows a mean ($\mu$) and standard deviation ($\delta$) from the Morris method, as well as a new parameter, lambda ($\lambda$), to be determined for the input factors of the model. The mean allows the overall influence of the factors to be determined, while the standard deviation identifies factors with possible interactive effects. The new term, lambda, provides a global sensitivity measurement for 2-factor interactions [7]. The software requires the identification of the input factors, and the range of values to be set for these factors (Table 1), number of