MATHEMATICAL MODEL OF THE FLUID CATALYTIC CRACKING FOR WORK IN TESTING CONTROL SYSTEMS FOR THE CRACKING PLANT

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The goal of this work is modeling of the fluid catalytic cracking plant for using in testing new control systems for the cracking plant.

In recent years, environmental regulations caused that the FCC units have found very important roles in oil refineries for improve the quality of oil products. Catalytic cracking is perhaps the heart of the modern petroleum refinery. The large volume of oil handled even a small increase in efficiency pays important dividends in terms of energy saving and profits. Tighter and more efficient control of catalytic cracking plants is therefore now an important objective.

The model exhibits the behavior expected for a cracking plant based on reported commercial scale results and previous simulations. The model should be useful for future work in developing control systems for the cracking plant. Comparison of model prediction data with industrial ones shows that the model has been achieved adequately.

Because the simple distillation of crude oil, production amounts and types of products that are not consistent with those required by the market place, subsequent refinery process change the product mix by altering the molecular structure of the hydrocarbons. One of the way of accomplishing this change is through "cracking" a process that breaks or cracks the heavier higher boiling- point petroleum fractions into move valuable products such gasoline, fuel oil and gas oils. The two basic types of catalyst are thermal cracking. Typical temperatures are from 480°C - 540°C at much lower pressure of 1-3 atm.

The three types of catalytic cracking process are moving – bed catalytic cracking, thermoform catalytic cracking (TCC) and fluid catalytic cracking (FCC).

The FCC unit consists of the reaction section and the fractionating section that operate together as an integrated processing unit. The reaction section includes two reactors, the riser reactor, where almost all the endothermic cracking reactions and coke deposition on the catalyst occur, and the regenerator reactor, where air is used to burn of the accumulated coke. The regeneration process provides, in addition to reactivating the catalyst powders, the heat required by the endothermic cracking reactions.

In the FCC unit process, the catalyst enters the riser as a dense bed, it is accelerated by the dispersion steam and gas oil feed fraction that vaporized, and it is pneumatically conveyed upwards by the vaporized gas oil feed. During conveying, the catalytic cracking of gas oil feed is completed through efficient catalyst and gas contact.

This paper presents a mathematical model of modern FCC plant consisting of a riser cracker and a regenerator. The model is intended for use in tasting proposed control systems rather than for delaited design or optimization. Its goal, therefore, is to reproduce the general dynamical behavior of the cracker-regenerator system without modeling every mechanical detail of the plant.

The FCC plant consists of the reactor where gas oil feed is cracked to gasoline and a regenerator where carbon is burned off the spent catalyst. Modern catalysts are so active that cracking is essentially completed in the riser leading to the reactor vessel. The reactor acts mainly to separate catalyst from reaction products. The cracked products go to a fractionating system for separation into gasoline, light gases and heavier products. The fractionators cab have interactions with the cracker that are important in optimizing the whole process. The present model concentrates on the dynamics of the cracker-regenerator and doesn't include the fractionation system.

Carbon is burned off the step catalyst in the regenerator. Regenerated catalyst returns to the reactor carrying sufficient heat to supply the heat requirements of the endothermic cracking reaction. Catalyst is replaced continuously at a low rate to maintain average catalytic activity in the face of slow permanent deactivation. The plant operates within a fairaly narrow "window" of operating variables determined by constraints such as maximum oil feed rate, maximum circulation rate of catalyst, maximum capacity of regenerator air blowers, maximum reactor temperature and maximum regenerator temperature. Within these contraints the system has a natural stability with changes in the heat requirements of the reactor being compensated over a period of time by changes in carbon burnoff rate in the regenerator.

The cracking reaction is quite complex, reactions of many chemical species. In this research we use the "three lump" model to describe the kinetics in an approximate but realistic way. The chemical species are combined or lumped into three pseudo-components: gas oil, gasoline, and light gases/carbon. The reactions can then be represented by

Reaction 1: $F \xrightarrow{k_1} G$

Reaction 2: $G \xrightarrow{k_2} L$

Reaction 3: $F \xrightarrow{k3} L$

where F is feed (gas oil), G is gasoline and L are light gases.

The cracker model simulates a modern fluid catalyst riser cracking reactor. The model treats the riser as an adiabatic plug flow reactor. It is a quasi-steady-state model in that it neglects changes with time during passage of feed through the riser.

The cracker model consists of the following material and energy balances:

Material balance on gas oil:

$$\frac{dy_f}{dz} = -R_1^0 * t_c * [COR] * \Phi_0 * y_f^2 * \exp\frac{-E_f}{R * T_0 * (1+\theta)} * \exp(-\alpha * t_c * z)$$

Material balance ob gasoline:

$$\frac{dy_g}{dz} = -R_1^1 * t_c * [COR] * \Phi_0 * y_f^2 * \exp\frac{-E_f}{R * T_0 * (1+\theta)} * \exp(-\alpha * t_c * z) -$$

$$- R_2^0 * t_c * [COR] * \Phi_0 * y_g^2 * \exp\frac{-E_g}{R * T_0 * (1+\theta)} * \exp(-\alpha * t_c * z)$$

Energy balance (assuming adiabatic operation)

$$\frac{d\theta}{dz} = \frac{\lambda * \Delta H_f * F_0}{T_0 * (F_s * C_{ps} + \lambda * F_0 * C_{po} + (1-\lambda) * F_D * C_{pD})} * \frac{dy_f}{dz}$$

The regenerator model treats as perfectly mixed thank. Modeling started with a typical dense phase, bubble region and jet description of the regenerator but showed that this is the same form mathematically as the completely mixed tank formulation. In fact it reduces to the perfectly mixed tank when typical commercial parameters are substituted. The equations include a balance on carbon on the catalyst, an oxygen balance and energy balance. Time is the independent variable and the balances are for unsteady state.

Balance on carbon on catalyst:

$$\frac{d}{dt}(W * C_{RC}) = F_s * (C_{SC} - C_{RC}) - k * y_\infty * C_{RC} * W$$

Oxygen balance:

$$\frac{d}{dt}(W_a * y_\infty) = R_A * (y_i - y_\infty) - \frac{1+1{,}5 * \sigma}{M_c * (1+\sigma)} * k * y_\infty * C_{RC} * W$$

Energy balance:

$$\frac{d}{dt}*[T_{rg}*(W*C_{ps})] = T_{ri}*F_s*C_{ps} + T_a*F_a*C_{pa} - T_{rg}*(F_s*C_{ps} + F_a*C_{pa}) -$$

$$-(\Delta H_{CO} + \frac{\sigma}{1+\sigma}*\Delta H_{CO_2})*\frac{k*y_\infty*C_{RC}*W}{M_c}$$

The reactor and regenerator equations were combined into a model of cracking plant. In this simulation the pressure was assumed to be maintained constant in both riser and regenerator. It was also assumed that an effective level controller maintained the catalyst holdup in the regenerator constant. To solve the model equations the regenerator equations were first integrated numerically for a short time interval. This was followed by integration of the reactor equations to yield new process variables for the next time-step integration of the regenerator equations. This alternate integration for reactor and regenerator was continued to yield a prediction of the dynamic behavior of the cracking plant.

The time lag associated with passage of the feed though the riser reactor was neglected in this process. It is, therefore, negligible compared to the time constant (on the order of hours) for changes in the regenerator. Because the regenerator equations were stiff, the MATHLAB software package was used for their integration. The riser equations were integrated by a four-order Runge-Kutta subroutine.

A new simulation of the cracker-regenerator combination has been derived. The cracking reactor is treated as a plug flow reactor in agreement with modern riser reactor behavior. Simulations show the usefulness of the model in reproducing cracking plant behavior. The model should be useful for future work in developing and testing new control systems for the cracking plant.

NOMENCLATURE

y_f - weight fraction gas oil in vapor in riser

Z - dimensionless distance variable

R_1^0 - rate constant for gas oil cracking

R_1^1 - rate constant for gasoline formation

R_1^2 - rate constant for carbon formation

COR – catalyst to oil weight ratio

Φ_0 - activity of catalyst at riser inlet

E_f - activation energy for gas oil cracking

T_0 - temperature of feed at riser inlet

θ - dimensionless temperature variable

t_c - catalyst residence time in riser

α - catalyst decay rate constant

y_g - mass fraction gasoline in vapor in riser

E_g - activation energy for gasoline cracking

λ - weight fraction of gas oil in feed stream (gas oil plus steam) to riser

ΔH_f - heat of reaction of gas oil cracking

F_0 - mass flow rate of feed (oil + steam) to riser

F_s - circulation rate of catalyst

C_{ps} - heat capacity of catalyst

C_{po} - heat capacity of oil

C_{pD} - heat capacity of dispersing steam

W - catalyst holdup in regenerator

W_a - air holdup in regenerator

C_{RC} - weight percent of coke on regenerated catalyst

C_{SC} - weight percent of coke on spent catalyst

F_s - circulation rate of catalyst

k - carbon burning rate catalyst

y_∞ - oxygen mole fraction in regenerator

σ - CO2/CO ratio in flue gas from regenerator

M_c - coke molecular weight

T_{rg} - temperature of catalyst leaving regenerator

T_{ri} - temperature at riser outlet

T_a - temperature of air to regenerator

F_a - mass flow rate of air to regenerator

ΔH_{CO} - heat of formation CO

ΔH_{CO_2} - heat of formation CO2

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