Technology leveraged continuous process analysis to Optimize the performance of cracking furnaces

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Key points:
- Finding overall optimum operating conditions in the maze of conflicting sub-objectives
- Continuous technology leveraged analysis of plant operating data by experts
- Field adjustments for relaxing operational constraints

ABSTRACT

To get the best out of available assets, it is imperative to maximize operating efficiency. Ethylene manufacturers look for maximizing the quantity of feedstock and obtain the best overall yield of ethylene, while consuming the least amount of energy. These three sub-objectives often require implementation of directionally conflicting measures. For example, cracking at high severity increases per pass conversion of ethane to ethylene, thereby minimizing the quantity of recycle-ethane to furnaces and making available higher residual capacity for processing fresh feedstock. However, assuming that ethane is cracked to extinction, this is not the best strategy from the point of view of efficient usage of feedstock as it reduces ultimate ethylene yield. It also reduces furnace run-length and the consequent increased stoppages for decoking reduce the availability of this high-cost asset for production.

Determination of the optimum operating point for maximizing profit involves a compromise between the individual sub-objectives and is a function of the relative prices of raw material and energy and the physical condition of various sections of the manufacturing facilities at any given time, which impose constraints on the rate of processing. Even after the advent of sophisticated tools such as Advanced Process Control and Real Time Optimizers, which has facilitated operation near optimum conditions, there still exists a gap, which can be identified, captured and translated into additional profits through continuous remote analysis of plant operating data by experts in the field, who are empowered with state-of-the art tools involving a combination of process simulation, statistical modeling, artificial neural networks, linear programming, mixed integer and non-linear programming, etc. Simultaneously, appropriate adjustments are carried out in the field for relaxing some production constraints.

Such an approach is being effectively incorporated at several olefin facilities and has helped glean substantial benefits.

Introduction

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Thermal cracking of paraffinic hydrocarbons in presence of steam is a widely used process for making Ethylene. A variety of feed-stocks ranging from light gases like ethane, propane and butane to liquids like naphtha and Natural Gas Liquid (NGL) are commonly used. Ethylene and other products are formed in the cracking furnace itself; the downstream process focuses on separation of the main products from by-products and subsequent purification for meeting sales specifications.

The main reactions leading to the formation of Ethylene and Propylene involve breaking of carbon-carbon bonds and dehydrogenation, both of which are endothermic in nature. The heat of reaction is supplied by direct firing in heaters, which are referred to as cracking furnaces. A temperature of around 800 to 850 ºC is typically maintained on the process side at the furnace outlet.

At such high operating temperatures, undesirable condensation reactions that lead to the formation of coke are inevitable. Over a period of time, this coke builds up on the inner surface of the furnace tubes, causing additional resistance to heat transfer. To overcome this and still achieve the desired operating temperature, harder firing is resorted to in the cracking furnaces. This continues until one of the End-of-Run (EOR) criteria is reached, forcing the stopping of the furnace to carry out decoking to bring the furnace back to healthy condition.

For carrying out decoking, hydrocarbon feed is cut off and the coke is burned off using a mixture of steam and air. Decoking is an energy intensive operation as steam and fuel gas are consumed while no products are being produced in the furnace. Hence, higher the frequency of decoking, lower is the availability of the furnace for regular production and higher is the specific energy consumption. Some plants have the luxury of having an installed spare furnace, so that one furnace can be taken off line without limiting plant throughput. However, this is generally not the case. Installation of spare cracking furnaces is highly capital intensive. The emphasis, therefore, is on making the best use of available assets by improving the on-stream time.

Need for sophisticated analysis for continuous optimization of cracking furnaces

Profitable operation of Ethylene plants calls for maximizing production volumes while minimizing production costs. To achieve this, efforts are directed towards maximizing feed rates, improving yields of main products and decreasing specific energy consumption. Quite often, the changes in operating parameters required for achieving each of these sub-objectives, conflict with one another. For example, in an ethane cracker, to accommodate more and more fresh feed, it is possible to increase the cracking severity in order to maximize the conversion of ethane to ethylene at one go, so that the recycle ethane stream takes up only a small portion of the processing capacity. However, assuming that ethane is cracked to extinction, this strategy does not result in the most efficient use of feed as the ultimate yield of ethylene per unit of fresh feed processed is lower. Another downside of maintaining higher cracking severity is faster rate of fouling of the furnace, which implies more frequent stoppages for decoking and consequent reduced availability for production.

Several plants have implemented Advanced Process Control and Real Time Optimizers to facilitate operation near optimum conditions. However, in a dynamic real-life situation, there are so many parameters changing simultaneously that affect the optimum operating strategy e.g. raw material, energy and product prices, feedstock quality, feed availability, product inventories, equipment health on account of fouling or corrosion, etc.

Day-to-day Plant Optimization

Modern tools and techniques using a combination of process simulation, statistical modeling, artificial neural networks (ANN), linear programming (LP), mixed integer linear programming (MILP), mixed integer non-linear programming (MINLP) and goal programming, as appropriate for a given situation, enable optimization with multiple objectives. When such state-of-the-art tools are coupled with expert analysis and field adjustments, the benefits are significantly magnified. This paper discusses some approaches that have yielded good results across several olefins plants.

(a) Homogenizing the quality of feedstock

The quality of feedstock affects the yield of ethylene. Optimum operating conditions change with change in feedstock quality. To realize the benefits from operating at the optimum conditions, it is imperative that the feedstock quality remains consistent over a reasonable time period. Where there is no direct control on the upstream supplier and large variations in feedstock quality have to be dealt with, conscious efforts to homogenize the feed are needed.

For ethane crackers, the purity of ethane is critical. The main impurities are either lighter components like methane or heavier constituents such as propane. Variations in the proportion of such impurities with respect to time often result in sub-optimal cracking conditions, which adversely affects ethylene yield. One option is to purify the feed upfront using a demethanizer and/or depropanizer, as appropriate. However, considering the capital investment and energy requirements, such facilities are not always economically justifiable. It is cheaper to establish the optimum cracking conditions as a function of feed purity and keep adjusting these parameters continuously.

A similar situation exists in naphtha crackers. One solution is to homogenize the naphtha feed to crackers by blending different parcels in predetermined proportions. The degree of success of this approach largely depends upon the availability of storage tanks with good mixing facilities. Merely pumping two or more parcels of different qualities of naphtha in a fixed proportion into a common tank doesn’t help to any great extent, particularly if the tank diameter is very large, as there is a natural tendency to form layers of different densities inside the storage tank.

Case Study 1

A petrochemical complex, located near a port, has two naphtha cracking plants. The feedstock is imported using the sea route. The parcel size and quality of naphtha vary from consignment to consignment. The plant has six storage tanks, two of which are large while the other four are small. Interconnecting piping and pumping facilities allow transfer of naphtha from these tanks into some of the other tanks. Naphtha brought in by ships can be unloaded only into the two large tanks. When advance information on the estimated ship arrival date and parcel size is available, a part of the existing inventory in one of the two large tanks has to be transferred to other tanks to create adequate empty space for unloading the next parcel into a single tank and facilitate confirmation of the quantity transferred, by tank dip measurements. Only two of the smaller tanks have mixing nozzles for blending of different parcels. Three of the six tanks have the provision for being lined up to the pumps supplying naphtha to the two consuming plants.

The objective was defined as minimization of the standard deviation of the total paraffin content in the feed to each cracker over a five-day period. An LP model was built to determine the optimum inter-tank transfer schedule in the backdrop of the desired operating flexibility (max. number of changeovers per shift) and constraints imposed by the hardware. A sample output of the model is presented in Figure-I.

(b) Optimizing feedstock procurement strategy

The optimization problem becomes even more complex if the cost of raw material is a function of quality. It is an established fact that in naphtha crackers, the total paraffin content as well as the relative proportion of normal and iso-paraffins in the feedstock impacts ethylene and propylene yields. So, given a choice between naphtha parcels with different total paraffin content or different ratios of normal to iso paraffins, a decision has to be made in respect of the maximum premium that can be paid for a superior grade. Similarly, in gas crackers, the price of ethane feedstock is sometimes linked to its purity. Some operators use furnace yield prediction models for this decision making, but a more holistic picture can be obtained by using a model that considers all constraints in the downstream sections of the plant as well because the yield pattern in the furnaces determines which production constraint is likely to be reached first, which will restrict the total throughput. The ideal model allows changing of plant constraints depending upon the condition of various sections of the plant such as the extent of fouling, recycling strategy, etc.

(c) Optimizing Raw Material Conversion

In ethane cracking furnaces, the conversion of ethane to ethylene is a function of cracking severity. If the severity is low, the conversion per pass is low. The unconverted ethane is recovered in a downstream section of the plant and recycled back to the furnaces for cracking. If this ethane is cracked to extinction i.e. the unconverted portion from the second pass is once again recycled back for a third pass and so on until all ethane is converted to ethylene, the ultimate yield of ethylene, which is the main product, is fairly high. However, this comes at an additional cost of energy as the unconverted recycle stream has to be once again raised to the cracking temperature, quenched, compressed and separated from the main product. The recycle stream also takes up a part of the capacity in each of these sections of the plant, thereby limiting the residual capacity for processing fresh feed. The optimum conversion is a function of several factors such as feedstock availability, feed quality, downstream operating constraints and prices of raw materials, energy and finished products. Further, the current state of each furnace, particularly with respect to the number of days that it has been on line since the previous decoke, also affects conversion.

Case Study 2

The complexities described in (b) and (c) above were captured in a LP model, which was designed to churn out the distribution of feedstock between various available furnaces and determine the optimum operating conditions in each furnace such as Coil Outlet Temperature, Steam to Hydrocarbon Ratio, etc. (refer to Figure-II). It was demonstrated in commercial size plants that utilization of such tailor-made models on a regular basis brings about a 1 - 2% increase in overall ethylene production without any hardware modifications.

(d) Maximizing Furnace Throughput

When plant throughput is constrained by furnace capacity, particularly during periods of decoking or maintenance of one or more furnaces, it is desired to run the available furnaces flat out and squeeze in that last drop of feed until some design or safe operating limit is reached, which precludes pushing it any further. Field adjustments can help raise the bar.

Case Study 3

A trial was undertaken on a freshly decoked naphtha cracking furnace with a view to maximize the furnace throughput and sustain that operation for a prolonged period at the high severity required to obtain the targeted ethylene yield. Safe operating limits were fixed upfront. As the feed rate was raised, the firing of fuel gas required for maintaining the set Coil Outlet Temperature (COT), also increased. Initial hurdles such as low oxygen in flue gas and high Tube Metal Temperatures (TMT) were taken care of by making suitable manual adjustments to the air registers of individual burners, stack damper and fuel gas flow to individual burners. It was felt that on increasing the firing rate beyond a point, the skin temperatures of the convection section tubes would reach the design limits and be the first major constraint to be hit, so a mathematical model was built for estimating the skin temperatures of each row of the convection section tubes, based on heat balance across each row of tubes (refer Figure-III). Temperature and flow measurements on the process side and flue gas side were used as inputs to the model. As expected, the skin temperature limitation was reached but the furnace throughput could still be stretched further by increasing the flow of atemperation water and making use of the provision to inject secondary steam into the high temperature convection shock tubes at the base of the convection section.

(e) Improving Ethylene Yield

Ethylene yield is influenced by the partial pressure of hydrocarbons in the furnace coils. In general, cracking reactions that result in the formation of ethylene and propylene take place in the vapour phase and involve increase in the number of moles. Therefore, higher yield of main products is obtained at a lower partial pressure of hydrocarbons.

Case Study 4

One of the means of achieving lower partial pressure in the cracking furnaces is to reduce the total operating pressure by lowering the set point of the cracked gas compressor (CGC) suction pressure. A trial was conducted along these lines in an ethane cracker. The results achieved are presented in Figure-IV. As seen therein, the incremental yield benefit is more pronounced at lower operating pressures.

However, the savings arising on account of an increase in product yield were offset by the increase in compression ratio and consequent higher power consumption in the CGC. The optimum operating point was, therefore, determined after taking into account relevant hardware constraints and operating limits such as minimum suction flow to compressor, maximum continuous speed of rotation and maximum steam consumption in the turbine and based on the prevailing prices of raw material and energy. The plant was operated continuously at the optimum point.

(f) Predicting and Stretching Furnace Run Lengths

The quality of decoke plays a vital role in determining the number of days for which a furnace can run continuously before the next decoke. If the throughput to a furnace is more or less steady and the day-to-day variation in quality of feedstock is not very significant, it is possible to predict the run-length of a furnace with great accuracy based on field measurements of key parameters such as TMTs, COT and COP.

Case Study 5

Historical operating data for the past two years for four identical furnaces showed a large variation in run-lengths, ranging from minimum of 15 days to a maximum of 85 days. Some key operating parameters that could possibly affect run-length were identified and data on the change in each parameter was plotted across different run-lengths. One example is a plot of Tube Metal Temperature as a function of Furnace Run-length. Each run-length was analyzed to identify similar runs / patterns for different furnaces. Common patterns were identified and compared with a re-clustering result over the complete data set, covering all furnaces. Six distinct clusters were apparent, as shown in Figure-V. For each of these six clusters, a set of dependent variables was found and an ANN model was built. These models are auto learning type i.e. they learn from each new run. The initial five days' data was taken as the base period for re-training the model. Finally, an overall model, which is essentially a combination of the six individual models, was built to accommodate runs lying in-between the identified six distinct runs.

The rate of change of these key variables in the first few days of operation of a freshly decoked furnace is adequate to determine which particular pattern is being followed in that run. This information, along with the actual values, is then fed to the ANN model. The model estimates the dates when the operating parameters are expected to hit operating limits. The information provided by such models is very handy for scheduling furnace outages for decoking and carrying out other maintenance activities. This helps in overcoming a furnace operators' nightmare when more than one furnace reaches end-of-run criteria simultaneously, necessitating reduction of plant throughput.

Case Study 6

Statistical analysis of historical data revealed that from amongst various end-of-run criteria, high TMT was by far the most frequent cause for taking a furnace off-line for decoking. Field measurements showed that the TMT of all coils did not rise at the same rate. However, if the TMT of any one coil exceeded the maximum limit, the furnace had to be stopped for decoking. TMTs were, therefore, monitored daily, right from the start of run and whenever any particular coil showed an accelerated rate of rise of TMT, appropriate actions such as re-distribution of the heat flux, adjustment of hydrocarbon flow rates in individual coils, adjustment of steam to hydrocarbon ratio, etc. were taken (refer Figure-VI). These preemptive actions ensured a more uniform coking rate, reducing the spread between the coking rates of individual coils (refer Figure-VII). The end result was longer run-lengths between successive decokes, by as much as 50%, which in turn translated into additional plant throughput.

Results

Implementation of a combination of the actions described above has resulted in creating new daily, monthly and annual production records at many plants. Typical savings achieved by adopting this approach are in the range of 1 to 5 million USD per annum, without making any capital investments for hardware modifications. The achievements at one such ethylene plant are presented graphically in Figure – VIII.

Abbreviations used

ANN	Artificial Neural Network
COP	Coil Outlet Pressure
COT	Coil Outlet Temperature
EOR	End Of Run
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
NGL	Natural Gas Liquid
NLP	Non-Linear Programming
SOR	Start Of Run
TMT	Tube Metal Temperature