DESIN AND SETUP A COMPUTER CONTROL PILOT PLANT FOR THERMAL CRACKING EXPERIMENTAL STUDIES

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Abstract: Thermal cracking of hydrocarbons from ethane up to gas oil is one of the most important processes for production of olefins, the basic feedstock for the petrochemical industry. The key to successful process control in the manufacture of ethylene is temperature control of thermal cracking furnaces. This paper describes a computerized thermal cracking pilot plant and its capabilities for experimental studies. A computer program was developed for the monitoring and control purposes. By using a mathematical model, which describes the static operation of the pilot plant, a simulator was developed. This model is used to predict the steady state profiles of gas temperature and product yield. The effects of coil outlet temperature (COT) on product yield were investigated by simulation and experimental studies. The results show good agreement between simulation results and the experimental data.

Introduction

There are several processes which may be used in ethylene production, but the process favored in modern industries is the cracking reactions, also called steam cracking or pyrolysis. In this process hydrocarbon feed stock mixed with process steam are introduced into tubular reactors (cracking coils) with short residence time and high temperatures. Steam is used to increase the olefin selectivity and to reduce coke formation by decreasing the hydrocarbon partial pressure.

The paraffinic feedstock is thermally cracked into mainly olefins, aromatics, methane and hydrogen. The homogeneous cracking reactions are endothermic and need energy input in order to reach gas temperatures as high as 800 – 900 ^{oC} at the coil outlet. The required energy is supplied by thermal cracking furnace. In fact, hydrocarbon feed is mixed with steam in the convection section of the furnace and the temperature of the mixture is raised to the cracking temperature. The mixture is then fed into the radiant section of the furnace where the temperature of the gas mixture rises rapidly to the desired cracking temperature. In the radiant section, the hydrocarbon is cracked into olefins, aromatics, pyrolysis fuel oil and other hydrocarbons. Upon leaving the radiant section of the furnace the cracked gas is cooled rapidly to stop the undesired reactions [1].

Coil Outlet Temperature (COT) is an important parameter affecting yield of ethylene production and therefore it should be controlled. Since furnaces are the first step in the process, COT is controlled by measuring the cracked gas temperature in the coil outlet and manipulating the heat input to the furnace. This loop is one of the most important loops in the control of thermal cracking furnaces.

To investigate the effects of different parameters on products yield, a pilot plant is designed and constructed. In this work the effect of temperature is studied. In the first section a

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review on thermal cracking pilot plants is presented. Next the designed pilot is described. In the third part simulation program is described shortly and finally experimental studies and pilot plant design are explained and the results of the simulation are compared with the experimental and industrial data.

Literature Review on Thermal Cracking Pilot Plants

For designing the pilot plant we reviewed the literature regarding experimental setup of thermal cracking of more than 30 universities and research centers from different countries. These experimental setups were divided into bench and pilot scales. The bench scales are used to study thermal cracking kinetics, coke formation and coke deposition. The pilot scales are used for simulation of industrial conditions.

Bench scale experimental setups

In 1976 Albright and his coworkers in Purdue University used a tubular reactor for thermal cracking studies of propane. The diameter of reactor is 0.25 – 0.125 inch and was made from SS-304. Reactor was in helical form with 6.5 inch diameter and 180 inch length which was hold in a furnace with 700^{oC}. The residence time of the reactor was 2.5 sec. Propane pyrolysis and coke formation mechanism was studied by this setup. Since 1977 till 1988 Albright and his coworkers by changing the material, residence time and diameter of the reactor, extended their studies for thermal cracking of ethane.

In 1972 Shau and his coworkers in Pitsburg University used a similar tubular reactor for thermal cracking studies of normal nonane. For uniform temperature distribution along the reactor, the furnace was divided into 3 parts which could be heated independently and controlled by tiristors. The reactor wall temperature was measured in 6 points by alomel-cromel type thermocouplels.

In 1973 Hirato and Yoshioka used a tubular reactor and the furnace was divided into 6 parts which could be heated independently and controlled by an automated system.

In 1979 French and his coworkers in Goodyear Company used a tubular reactor for thermal cracking studies of methyl pantene. In this system feed and water as a diluting agent enter the preheaters through two infusion pumps and preheated to 500^{oC}. The effluent of preheaters is then mixed with hydrocarbon and enters the cracking reactor. Reactor effluent is then cooled rapidly and heavy products are separated from light products. Finally a sample of light products is sent to the analyzing section. In 1982 Froment and his coworkers used the same system for ethane and naphtha thermal cracking studues. In this system the feed flow rate was 12 gr/hr for ethane and 40 gr/hr for naphtha.

In 1982 Holman and his coworkers in Norwegian Institute of technology, 1979 Leonard and Gwyn in Shell research Institute of Texas, Ghaly and his coworkers in Oklahoma State University, 1982 Brown and his coworkers in British Petroleum Company, 1982 Sacco and his coworkers in chemical engineering department of Worchester University, 1985 Kumar and Kunzru in Indian Institute of Technology, 1987 Renjun and Lou in Hebei Institute of Technology of China, 1988-1993 Kopinke and his coworkers in Leipzig University of Germany, 1988 Koltz in Phillips Oil Research Center of Oklahoma, 1985-1989 Depyre and coworkers in French, 1995 Reed in Phillips Oil Research Center of Oklahoma and 1997 Choudhary and his coworkers in India used the similar system and studied the thermal cracking kinetics of various feed at different operating conditions [2].

Pilot scale experimental setups

In 1982 Froment and his coworkers in Gent University of Belgium used a semi industrial scale tubular reactor to study the thermal cracking process. This pilot plant had special facilities for research purposes. The length and diameter of reactor was 21.75 and 0.01m respectively and was held in a combustion chamber with 4m length, 0.7m width and

2.6 m height. The furnace was divided into 7 sections and heated by 90 burners which were arranged in furnace walls. Therefore any desired temperature profile could be applied to reactor by using an automated control system. The two first sections of furnace have low temperatures (about 600^{oC}) and are used for feed prehating and the other sections have high temperatures (about 900^{oC}) which are suitable for thermal cracking reactions. 13 thermocouple have been used for measuring of the gas temperature inside the reactor and 14 thermocouple have been used for measuring of the skin temperature of the reactor. This pilot can be used for wide range of gaseous and liquid feeds from ethane up to gasoil. Reactor effluent is then cooled rapidly in a transfer line exchanger and heavy products are separated from lights and a sample of light products is sent to the analysis section which was equipped by 4 gas chromatograph analyzers. In this pilot an on line computer is used for analyzing the results [2].

The Linde company of Germany designed and constructed a pilot plant for the same purpose. The reactor of this pilot is 20m long with 0.006m diameter which has a helical form. The high voltage electrical power was directly connected to the pilot reactor and the required heat was generated for thermal cracking reactions. Feed preheating and analyzing sections are the same as aforementioned pilots. In quench section, injection of water to gaseous mixture is done instead of cooling by a heat exchanger [2].

The Thermal Cracking Pilot Plant

By reviewing the above pilots, a pilot plant was designed and constructed for experimental studies of hydrocarbon thermal crackling. A simplified P&ID of the pilot plant is shown in Figure1. Six major parts may be distinguished in the pilot plant. These parts are: feed section, preheating section, furnace and reactor sections, quench section, analyzing section and computer control section which are described below.

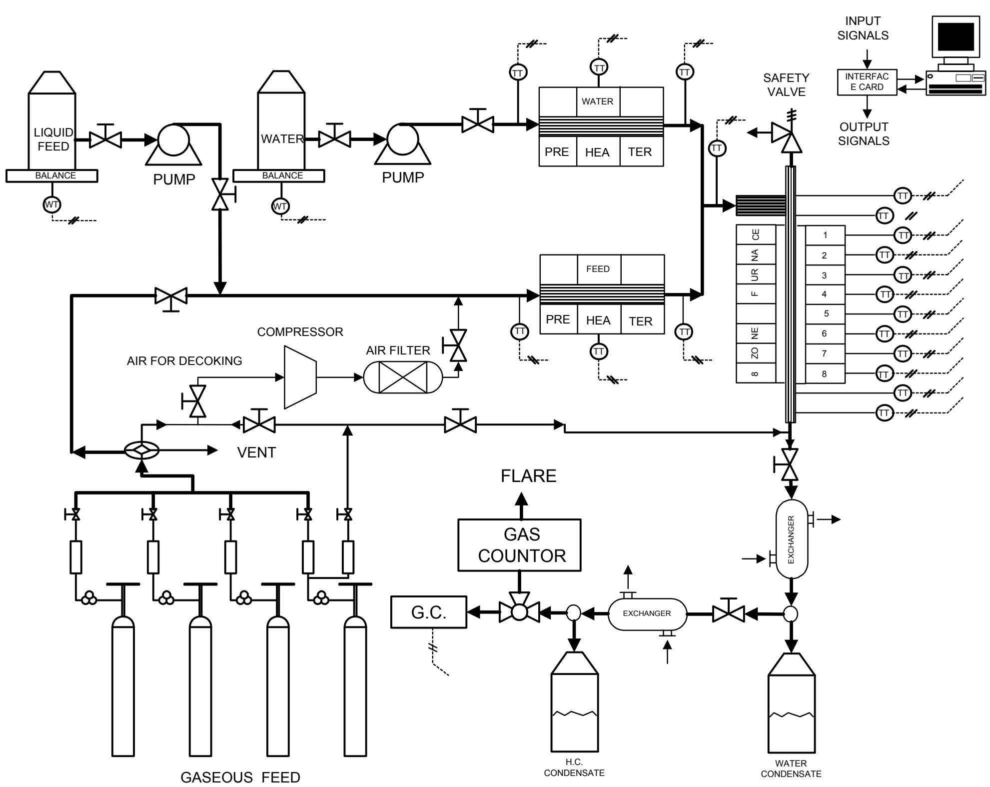

Figure 1: Schematic diagram of thermal cracking pilot plant

Feed section

This section contains at least two streams: hydrocarbon and the diluting steam. Both gaseous and liquid hydrocarbons can be fed. Liquid hydrocarbons and the water are fed by means of dowsing and pulsation-free pumps. Maximum flow rate and maximum outlet pressure of these pumps are 3 lit/hr and 10 atm respectively. The vessels containing the liquid feedstock are placed on digital balances which is connected to the computer for monitoring the flow rates. The set points of the pumps are set manually. The feed flow rate and steam/hydrocarbon ratio (S/HC) can be varied between 4 - 40 g/min and 0.3 – 0.8 respectively.

Preheating section

Preheating section consists of two electrical preheaters for preheating the water and hydrocarbon feeds up to 600^{oC}. The preheaters are single zone and the power of each zone can be controlled manually by tiristors or automatically by independent PID controllers. Maximum temperature of these preheaters is 900^{oC} and the maximum power is 13.2 kw. Length and diameter of each preheaters are 1m and 0.1m respectively. Three thermocouples are installed in each preheater for measuring the temperature. Feed and water interred to a 1m length tube made of stainless steel with internal diameter of 0.01 m. The inlet and outlet temperatures of feed and water are measured by thermocouples which are installed inside the tubes.

Furnace and reactor section

The pilot has an electrical furnace in the reactor section. The furnace is divided into eight zones, which can be heated independently and therefore any desired temperature profile can be applied to the reactor. Power of each zone can be controlled manually by tiristors or automatically by any control algorithm implemented through the computer control system. Maximum temperature of furnace zones is 1100^{oC} and the maximum power of each zone is 2.2 kw. The length and diameter of furnace is 1m and 0.1m respectively. 16 thermocouples (2 thermocouples per each zone) are installed in furnace for measuring the zone temperatures. The reactor feed (mixture of preheated feed and water) inters the reactor which is a tube with 1 m long made of inconel (alloy 600 H S 2), and has an internal diameter of 0.01 m. The inlet (cross over temperature-XOT) and outlet (coil outlet temperature-COT) temperatures of the reactor are measured by 2 thermocouples which are installed inside the reactor tube. Two pressure gages equipped with safety valves are installed in inlet and outlet of the reactor.

Quench section

In this section the gases leaving the reactor are cooled from 670^{oC} to 40^{oC} in a double pipe heat exchanger by using cooling water. Using a second exchanger which is a circulating water type, temperature of products is cooled close to 0^{oC}. The heat exchanger area is about 0.5 m^2. After cooling of gaseous product, liquids and tars are separated by means of three glass condensers. The pressure at the reactor outlet is controlled manually by using a pressure reducing valve. A fraction of the product gas is then withdrawn for the on-line analysis by Gas Chromatograph (GC), and the rest is sent directly to the flare after measuring its volume.

Analyzing section

The on-line analysis of the reactor effluent is performed by means of two computerized GC's, both manufactured by Varian Chrompack. The first one has two Flame Ionization Detectors (FID) and used for analyzing the light cracking components including light hydrocarbons up to C4, carbon monoxide and carbon dioxide. The second one is used for analyzing the heavy components including C5+ and aromatics or PIONA, hydrogen and methane. The specifications of two GC's are given in Table 1.

Table 1: Specification of analysis system

Chromatograph			
1.Varian Chrompack CP3800			
Column	**Type**	**Detector**	**Product analysis**
A	Capillary CP-CIL 5CB	FID	C_2H_4,C_3H_6,C_4H_6, …
B	Packed column	Methanizer and FID in series	CO, CO_2
2.Varian Chrompack CP3800			
A	Capillary CP-CIL-PIONA	FID With split/splittless	C_5+ , Aromatics
B		TCD	H_2 ,CH_4

Computer control system

All actions including start/stop of pumps, regulating and measuring of feed and water flow rates, temperature regulations of preheaters and furnace and temperature monitoring are performed manually by using a control panel or automatically through a computer controlled system.. Control, monitoring, data logging and alarm management are done in automated mode. Details of automated control system including hardware and software will be described bellow:

Hardware: The PIII-500 process computer is connected to the pilot plant through interface cards. Three different interface cards are used. One card receives the thermocouple signals and converts them to digital signals. The second card has 16 analog inputs which can be used for GC measurements and it has also 24 digital I/O that are used for on/off control (pumps). The last card which has analog outputs is used for temperature control. To control the temperature, heaters power is changed through analog outputs via tiristors. To monitor the feed mass flow rates, two serial ports (RS-232) are connected to the balances. The I/O list is given in Table 2.

Table 2: System's I/O list

Type of signals	Numbers	application
Analog Input	32	Thermocouples
Analog Input	16	GC's
Analog Output	10	Preheaters & Furnace
Digital Output	32	Pumps

Software: For on-line monitoring, control, data logging and alarm management of the pilot plant a software is developed. The specific applications of the software for this pilot plant are monitoring and control of furnaces, start and stop of pumps and monitoring of feed flow rates. Sample time can be set by the user. The minimum sample time is 0.1 sec. Trends of all variables can be shown and saved and alarm management is possible. Also PID control or user defined control algorithm can be implemented.

Pilot plant capabilities

The pilot capabilities can be listed as bellow:

1-Using liquid and gaseous feed in various ranges
2-Control of preheaters duty for temperature regulation of effluent streams
3-Control of furnace duty for temperature regulation of reactor effluent
4-Applying any desired temperature profile along the reactor
5-Applying PID or any user defined control strategies
6-Online analysis of products
7-Facilities for adding anti coke materials
8-Facilities for system decoking

Static Simulation of the Reactor

The heart of an ethylene plant is the cracking furnace. For finding an optimal operating strategy, it is necessary to investigate the influences of the operating parameters, which can be satisfactorily performed through the rigorous modeling. Kinetic model of thermal cracking reactions, mathematical modeling including mass, energy and momentum balances, suitable numerical method for solving differential equations and software are required for static simulation of thermal cracking reactors. In this work a free-radical reaction mechanism for naphtha thermal cracking has been used and also the rate of coke formation has been taken into account. The implicit Euler method is used for solving the equations and a software was developed for static simulation of the pilot plant. The developed software receives the feed specifications and operating conditions and calculates products yield and gas temperature profile along the reactor [2-14]. The details of static simulation of the pilot plant are presented in reference 3.

Simulation results

For comparing the simulation results with industrial data, the same industrial naphtha feed and industrial operating conditions are used in simulation program. The composition of naphtha feed is: 41.99% n-paraffins, 47.83% iso-paraffins, 7.01% naphthenes and 3.17% aromatics. Also the feed inlet temperature and pressure to the reactor are 600^{oC} and 3 atm respectively. Steam/Hydrocarbon ratio is 0.7, COT is 830-870^{oC} and the feed flow rate is 10 gr/min which is normalized by industrial feed flow rate and reactor size. After running the software program under these conditions, furnace temperature, gas temperature and products yield profiles are obtained along the reactor. Different isothermal temperature profiles are applied to the reactor and the simulation results at the reactor outlet are presented in Table 3. These results show that increasing COT, will increase the ethylene yield [3].

Table 3: Static simulation / experimental results

COT (^{oC})	C2H4 Yield (%wt)	C3H6 Yield (%wt)	Furnace Temp. (^{oC})
830/810	26.79/18	11.8/8	913/913
840/825	28.81/26.12	12.07/11	924.5/924.5
850/840	30.66/27.98	12.17/11.2	935.5/935.5
860/---	32.15/---	12.1/---	945.5/---
870/---	33.43/---	11.86/---	954/---

Experimental Studies

Experiments are performed with typical naphtha as feed which was supplied from ARak Petrochemical Company (ARPC). The feed flow rate and operating conditions are set to values as mentioned in previous section. Preheaters and the furnace temperatures are set to desired values by using PID digital controllers. To set the XOT at 600 ^{oC}, water and hydrocarbon preheater set points are set to 750 ^{oC}. By changing the furnace set point, different COT values will be achieved. While running the pilot under these conditions, the effluent cracked gas is sent to the GC for the analysis. The results of the experiments are presented also in Table 3. As can be seen, increasing the COT, increases the product (ethylene and propylene) yield. These results are also shown in Figure 2 and compared with industrial data. As can be seen all industrial, experimental and simulation results have the same trends [15].

XOT, COT, furnace temperature and furnace set point are presented in Figure 3. As can be seen the XOT is approximately constant at 600^{oC}. The COT is increased with increasing the furnace temperature. Fluctuations on COT is caused by the coke deposited on the COT measuring thermocouple. Furnace temperature tracks the furnace set point. The figure shows that at higher set points oscillations are increased. It may be due to nonlinear plant dynamic and using constant controller tunings. The results show that the controller performances are fairly well.

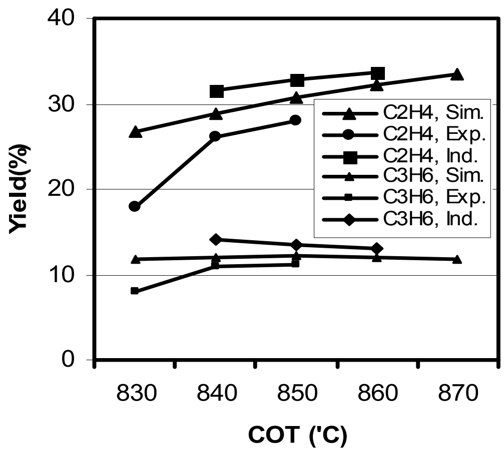

Figure 2: Effect of COT on the product yield

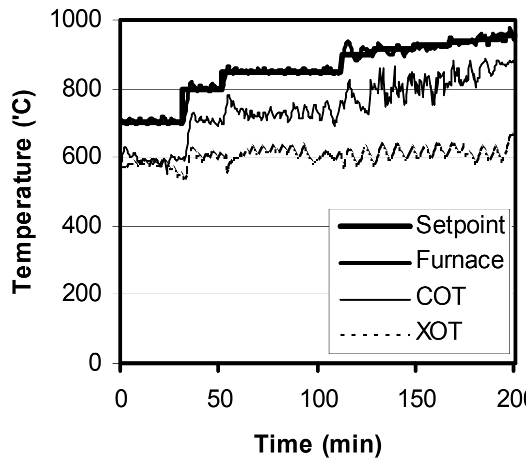

Figure 3: XOT, COT, furnace temperature and furnace setpoint

Conclusion

In this paper a thermal cracking pilot plant was described. Based on the kinetic model proposed in the literature, a computer program for simulating the plant is developed. The software program is used to investigate the effects of temperature on the product yields. Simulation results indicate that increasing COT, increases the ethylene yield. Simulation results were tested experimentally by the pilot. Comparison of simulation, experimental and industrial results shows that, they have the same trends. The discrepancies between industrial and simulation results refer to the reactor configuration and the discrepancies between simulation and experimental results are due to the nonlinear and unknown furnace model, and some measurement errors in experiments.

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