An automation and control methodology through model based predictive control (MBPC) for propylene maximization via fluid catalytic cracking (FCC) technology – A Review

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Abstract— *Oil refining is an industrial process which involves separation, conversion and refining. The fluid catalytic cracking unit (FCCU) is one of the most important and complicated process in the refining industry and it is the major conversion unit. FCCU is responsible for the production of gasoline, Liquified Petroleum Gas (LPG) and Light Cycle Oil (LCO). The catalyst performance and the advanced control system have contributed to increase the propylene production and to increase of the plant profit. One concept of advanced control is represented by model based predictive control. This review focuses towards maximizing the production of propylene. Maximization of propylene production has become the major focus of most refineries because it is high demand chemical and a supply shortage from modern steam crackers, which now produces relatively less propylene. The appropriate modification of the FCC process is accomplished by the synergistic integration of the catalyst, temperature, reaction-residence time, coke formation, and hydrocarbon partial pressure. The main constraints for maximizing propylene yields are based on having a suitable catalyst, suitable reactor configuration, and proper reactor conditions. The control of fluid catalytic cracking unit is complicated as it involves numerous parameters to be monitored and controlled. Hence, Distributed Control System (DCS) is employed to automate the FCCU Process. The topics approached in the paper are: the overview of the model based predictive control concept for FCCU, maximizing propylene yields based on suitable reactor configuration and reactions conditions, and study of distributed control system to automate the FCCU process.*

Keywords: Refining · Fluid Catalytic Cracking · Propylene yield · Control · Automation.

I. INTRODUCTION

Fluid catalytic cracking (FCCU) is a complex process, both from modeling and from the control point of view. The fluid catalytic cracking unit (FCCU) has become the "test bench" of many advanced control methods. The FCCU is difficult to control because: it includes the nonlinear character and the strong interaction between the variable of the process, the multivariable character and many operating constraints of the process, it also involve a large difference between time constants and very complicated and little known hydrodynamics of the process. It comprises of complex kinetics of both cracking and coke burning reactions. It is necessary to control system with changing operating conditions in presence unmeasured disturbances [3, 5].

Propylene maximization is the term refers to increase the amount of propylene extracted from the light olefins. Fluid catalytic cracking unit (FCCU), one type of conversion unit, it upgrades heavy hydrocarbons to lighter more valuable products by cracking and is the major producer of gasoline in refinery. Fluid catalytic cracking is a refinery process that can be used to produce gasoline and other distillate fuels from larger hydrocarbon molecules using catalyst. The catalyst is a solid zeolite material that is made fluid by the hot vapour and liquid is fed into FCCU. As the catalyst is fluidized due to heat it can circulate between reactor and catalyst regenerator. After the feed is cracked through contact with catalyst the resulting vapour is processed in fractionators, at which it separates the feed based on various boiling point into various intermediate products like lighter hydrocarbon, gasoline, light cycle oil, and slurry oil. The automation of fluid catalytic cracking process (FCC) is done by identifying the important parameters to be measured and controlled and modeling or designing the control loops for identified parameters. In fluid catalytic cracking unit, it is very important to control various process parameters like reactor temperature, feed flow rate, lift steam flow rate, hot generated catalyst temperature, spent catalyst temperature, feed temperature, reactor liquid level, catalyst regenerator temperature, catalyst regenerator air flow rate, light cycle oil flow rate, gasoline flow rate, stripping flow rate, and main fractionator top temperature. Using distributed control systems (DCS), transmitters and control valves are linked with the controllers [4]. The objective of this review is to evaluate the processing of hydrocarbon feedstock to maximize the propylene yield by existing FCC technology, and study while implementing a model based predictive control system and automate using distributed control system (DCS); as a reactor configuration and reaction conditions.

II. PROPYLENE MAXIMIZATION

Light olefins are important raw material in many petro-chemicals because they are building blocks for many end products, such as polyethylene and polypropylene. A large proportion of propylene is produced by steam cracking (SC) of light naphtha and during the fluid catalytic cracking (FCC) process [6].SC is an established technology for the production of light olefins, such as ethylene and propylene. It accounts for about 60-65% of the world's propylene production, with the established refinery FCC process accounting for 30% and the remainder is produced on purpose using metathesis or propane dehydrogenation [7].

With the ethylene and gasoline being the main product from SC and conventional FCC, respectively, propylene and other light olefins are obtained as by-products from these technologies. Propylene production from steam crackers depends upon the operating rates of the steam cracker and type of feedstock. Earlier, propylene was produced from steam crackers via heavy liquid cracking and as a result, it was readily available; however, most modern steam crackers use ethane-based feed in place of heavy liquids leading to less propylene being produced. It is expected that propylene production from steam crackers will be lower than the corresponding ethylene production as a results of the shift to ethane based feed. It can be seen that SC alone cannot satisfy the demand for propylene. Therefore, there is strong need of development of new technology to produce additional propylene to bridge the gap between supply and demand. With this purpose propylene production technologies, such as propane dehydrogenation and metathesis being as possible alternative, the cost associated with these technologies remain less competitive relative to steam crackers and FCC [1]. It could have been easier to fill the gap by reconfiguring the steam cracker, but the steam cracker does not provide flexibility of operation and it has high energy consumption and it is higher intensive process in the chemical industry which uses approximately 8% of the total global primary energy use, excluding energy content of final products.

According to Ren et. al., the pyrolysis section of a naphtha steam cracker alone consumes about 65% of the total process energy and contributes about 75% of the total energy loss. Being an essentially non-catalytic and non-selective process SC is energy intensive and catalysts have never been widely used in the pyrolysis section in SC to optimize energy efficiency. By adopting technologies based on the reconfiguration of the FCC unit to maximize the production of propylene and light olefins, it is expected that energy saving and flexibility of operation will be obtained because:

- FCC catalyst provides an alternative route to SC with the use of lower activation energy for Carbon-Carbon bonds rupture. Consequently, the temperature for the new catalytic naphtha cracking processes are 150-250 ^{o}C which is lower than those for steam crackers.
- Catalysts improve selectivity to desired products, such as propylene. Even if the same operating condition as those of SC is applied for catalytic cracking, the total olefin yield would still be enhanced by at least 15 %.
- Coke formed during the cracking process is constantly removed by catalysts that are in turn decoked through catalyst regeneration or catalyst decoking.
- FCC is one of the most flexible processes in a refinery and can readily adjust to changes in feed quality through modification to catalyst and operating condition [8].

The configuration of the FCC process, which involves a circulating fluidized bed with the availability of heat and mass transfer and catalysts regeneration, makes it possible for the FCC to be used for application that go beyond the upgrading of heavy feed to gasoline. In the FCC, light olefins are produced via catalytic cracking of hydrocarbon feedstock by contacting the feed with a catalyst usually consisting of one or more crystalline microporous molecular sieves to selectivity convert the feed into an olefin containing mixture. The propylene demand from FCC is growing at a faster rate than global FCC capacity and therefore propylene yields from FCC need to increases to keep up with demand. These three main factors called as the constraint triangle for maximizing propylene production as described by Maadhah [9].

III. VARIABLES THAT AFFECT PROPYLENE PRODUCTION

A. Reactor Configuration:

New FCC catalyst technologies are being developed to enable refiners to achieve the challenging propylene yields required to meet the growing demand for propylene from FCC. As results, various methods and configuration have been proposed for increasing or enhancing the outlet of propylene product stream from FCC unit. By taking into consideration the operating condition and yield of the FCC, the propylene yield pattern can be represented in the form of a continuum varying from ***operating severity to process design*** and these can be optimized to suit the refinery specific economics[10]. For refinery, maximizing gasoline yield is more important than the propylene yield, while for petro-chemical application, the target is operating at maximum propylene yield. Many FCC processes increase propylene by manipulating FCC reaction variables such as catalyst to oil ratios, residence times and reaction temperatures [11]. The modifications can be put into two categories: ***Up flow (Riser)*** and ***Down flow (Downer)*** technologies. In the riser reactors, solid catalyst and hydrocarbon vapours flow upwards against gravity. This upward flow results in a catalyst flow that id significantly slower than the lighter hydrocarbon leading to back mixing of the catalyst and as a result there is an increase in residence time of catalyst. This in turn can lead to undesirable secondary reaction leading to over cracking [1]. In contrast to riser, and to overcome the issues related to back mixing. The flow of the catalyst and the feed is in the direction of gravity and such, back mixing is largely avoided and there is an even distribution of catalyst with an effective contact time of catalyst and feed less than that of the riser. The FCC technology based on the downer design, and which is in commercial operations, is briefly described below. Downer FCC technology: high severity fluid catalytic cracking (HS-FCC). The HS-FCC process developed jointly by Saudi Aramco and partners is operated under considerably higher reaction temperatures (550 - 650^{o}C) than conventional FCC units and the main objective is to produce more propylene and high octane number gasoline. Under this condition, however thermal cracking of hydrocarbon also takes place concurrently with catalytic cracking, resulting in increased undesirable products as dry gas and coke. Short contact time (less than 0.5 s) of the feed and hydrocarbon in the downer minimizes thermal cracking. Undesirable successive reactions, such as hydrogen transfer, which consume olefins, are suppressed. To attain, short residence time, the catalyst and the products have to be separated immediately at the reactor outlet. For this purpose, a high efficiency, short residence time products have to be separator has been developed, and it capable of suppressing side reactions (oligomerization and hydrocarbon of light olefins) and coke formation[9,12,13]. Due to the short contact time, the conversion in HS-FCC mode is expressed to drop and to compensate this, the HS-FCC process is operated at a high C/O ratio and at higher temperature than conventional FCC process. The advantage of this operation at a high C/O ratio is the enhanced contribution of catalyst cracking over thermal cracking. High C/O maintain a heat balance and helps minimize thermal cracking, over cracking, and hydrogen transfer reaction. The synergetic operation of the reaction conditions, high C/O ratio and downer operation provides a yield of a high olefin [1].

B. Riser FCC technology & Riser Model:

Two technologies based on Riser FCC are deep catalytic cracking (DCC) and catalyst pyrolysis process (CPP), developed by SINOPEC.

- **Deep catalytic cracking (DCC)**

  DCC is derived from FCC and its flow scheme is similar to that of FCC consisting of a continuous reaction/ regeneration system with fluidized catalyst circulation. The main difference in hardware is a bed reactor installed after the riser. DCC uses FCC principles with specific enhancements to produce large yields of light olefins and high octane naphtha. To achieve a high olefin yield, a high reactor temperature is required. The DCC units operate at temperature as high as 570 ^{o}C, somewhat higher than maximum olefin FCC and residue FCC operations [14,15,16].

- **Catalyst pyrolysis process (CPP)**

  CPP is further modified from DCC aiming at more ethylene production. The modification includes new catalyst formulation, varied operating conditions and some changes on engineering [14]. CPP catalyst possesses the features of low hydrogen transfer reaction; higher matrix activity; active component consisting of both large pore and mesopore zeolite; higher hydrothermal stability. CPP operating condition is more severe than that of DCC. The reaction temperature is about 80 K higher, therefore it requires higher regeneration temperature to provide the heat of reaction; and both the stream dilution and catalyst to oil ratio are double. CPP uses a riser reactor and a cross current degassing device to minimize the flue gas adsorbed by the regenerated catalyst.

DCC and CPP use more stream than conventional FCC and their operation can be termed as steam catalytic cracking (SCC). The main feed for the SCC process so far has been naphtha or other light feed, but the amount of coke produced during cracking of naphtha is too low to produce heat by combustion to maintain the catalyst temperature. Therefore, extra heat will have to be supplied into the regenerator by burning off added hydrocarbon.

The FCC unit having the cylindrical vessel called riser, which is the main reactor, where the cracking reaction is taking place in the presence of catalyst. The catalyst, a mixture of crystalline alumina silicates (zeolites) is a sand like material which is fluidized into a fluid via contact with liquid fed into the FCC unit. A typical configuration of a FCC process consists of two major units; the riser and regenerator. The riser is modelled as plug flow and the vaporization of gas oil was considered to be instantaneous in the vaporization section. The hot regenerated catalyst meets the feed at vaporization section and vaporizes the feed with dispersion steam to move upward into the riser where the gas oil gets cracked on the catalyst and produces desirable products. The kinetic studies on the production of propylene have been carried out and they are mostly based on catalytic pyrolysis. Catalytic pyrolysis includes catalytic reactions and thermal reactions and the cracking extent of catalytic pyrolysis is more than that of catalytic cracking. Catalytic cracking is favored over thermal cracking for maximum propylene production especially in high severity FCC unit. Temperature varies in the riser and has effect on some important kinetic variable such as rate constant and catalyst deactivation, it means that heat required at every point in the riser varies [8,9,17].

IV. CHARACTERISTICS OF SOME FCC TECHNOLOGIES

Most of the new FCC based technologies for SCC make use of high Catalyst to oil ratio to promote catalytic cracking and reduce thermal cracking. Using a high Catalyst to oil ratio also that more heat is transferred from the regenerator to the reactor as the catalyst and oil will equilibrate at higher temperature in the reactor. Apart from the DCC, all the other techniques have shorter residence times in the reactor than normal FCC. For CPP and HS-FCC, which operate at higher temperature, the advantage of shorter residence time is to prevent over cracking, which for the DCC, a longer contact time is required to guarantee the cracking of the reactants. The HS-FCC process, more coke is produced showing that these processes are capable of achieving the heat balance needed during steady-state operation. Another observation is the fact that all the FCC based processes produce less gasoline, especially the CPP process. If the FCC based processes are fully integrated into the refinery system, there is a possibility of having a shortage of gasoline in the market. This requires that a balance be made between maximum propylene yield and gasoline supply. Gasoline produced is to look at using crude oil as feed so that refinery capacity should not be a restricting factor for the new processes. While propylene generation from an FCCU certainly varies with feedstock, it is primarily a function of catalyst type, reactor temperature, partial pressure, Catalyst to oil ratio and total pressure [1].

V. REACTION VARIABLES

A. Effect of contact time or catalyst circulation rate:

Residence time in the reactor varies according to the reactor configuration, reaction temperature, Catalyst to oil ratio and the intended product. The conventional FCC has a higher residence time distribution than the HS-FCC process. HS-FCC process uses a higher Catalyst to oil ratio, higher temperature and it is aimed at maximizing propylene production to prevent thermal cracking and hydrogen transfer reactions.

The feed conversion was about 98.5% and remains relatively constant with residences time. The yields of light olefins first went up until a residence time of about 2.0s, where they remained relatively constant.
Longer residence time indicates more time for catalytic pyrolysis of hydrocarbon, and pyrolysis extent was more thorough [1,18].

B. Effect of temperature:

A rise in temperature will increase the extent of catalytic cracking. In the reaction temperature is raised by raising the catalyst circulation. By using a higher Catalyst to oil ratio, the reaction rate of the catalytic cracking is improved and pyrolysis yield increases. Reaction with only short contact times will also control over-cracking. HS-FCC units operating at maximum propylene production use short contact time along with higher reaction temperature and higher Catalyst to oil ratio. This is to accelerate catalytic cracking, control the hydrogen transfer. Propylene and butylene are mainly generated through cracking mechanism via the carbonium ion. Intermediate products can under goes secondary reactions such as cracking and hydrogen transfer, at high temperature [1, 19].

C. Effect of Catalyst to oil ratio:

The amount of catalyst that contacts the feed will vary depending on the temperature of the regenerated catalyst and the severity of FCC process. A high Catalyst to oil ratio will operate to maximize conversion, which tends to favour light olefins production. The Catalyst to oil ratio is dependent on the heat balance limitation of the unit. A large Catalyst to oil ratio means that reaction will occur at a higher temperature as the catalyst and feed will equilibrate at high temperature as the catalyst and feed will equilibrate at high temperature. This means such energy can be transferred in the reactions. To a certain extent, a high Catalyst to oil ratio means a thorough pyrolysis as this can promote secondary reaction of light olefins and may affect production cost. The value of the Catalyst to oil ratio cannot be too high and should be optimized based on the FCC technology being used [1,20].

D. Effect of feed quality:

Feedstock that is high in aromatics has low hydrogen contact and resistant to conversion at typical FCC residence times. The production of propylene requires the hydrogen and co-products, including propane and dry gas requires. The amount of hydrogen available from the feedstock can limit the potential to produce propylene. Conradson carbon ends up the coke, thereby further reducing the potential propylene production. More propylene can potentially be derived from feed sources and feed sources rich in aromatic components produce resulting in potentially less propylene yields [21,22].

E. Effect of hydrogen transfer index:

The hydrogen transfer index is defined as the paraffin/olefin ratio of C_3, linear C_4 and branched C_4 species. The relative activity of FCC catalysts for reaction can be estimated using the hydrogen transfer index (HTI) for catalyst tested under constant conditions with the same feed. Hydrogen transfer by maximizing the available of olefin precursors is the key to maximizing propylene. Hydrogen transfer reaction involves the formation of bulky bimolecular reaction intermediates, due to the space available inside the micro-pores of the zeolites. They can also occur on the outer surface of the zeolite particles. The smaller the pore size of the zeolite, the greater the extent of the alkenes, which means that the HTI decreases with the pore size of the zeolite [22,23,24,25].

F. Effect of hydrocarbon partial pressure:

It generally expected that a rise in hydrocarbon partial pressure will increase the rate of all bimolecular reactions, including hydrocarbon transfer, relative to cracking, which is uni-molecular. An increase in the rate of hydrogen transfer will result in a reduction of olefins in both gasoline and LPG, and an increase in gasoline range aromatics and paraffin's. The change in the rate of hydrogen transfer could also affect the gasoline sulphur concentration as well as the effectiveness of gasoline sulphur reduction catalysts and additives. The raising the hydrocarbon partial pressure increased the amount of dry gas and coke at the expense of gasoline [26].

VI. FCCU PROCESS CONFIGURATION

The fluid catalysts cracking unit, presented in figure contains two components: the reactor and the regeneration. Because the modelling of the reactor is very difficult, decomposition of the process can be represented in four sub-processes below.

- Interfusion node sub-process is located at the reactor base and is designed for the instantaneous vaporization of the feedstock at direct contact with the regenerated catalyst.

- Riser sub-process is a plug flow tubular reactor where takes place the chemical reactions.
- Stripper sub-process, contains a cyclone system, assimilated to a reactor for the gaseous phase separator of the feedstock and the reaction products in the from the catalyst particles.
- Regenerator sub-process is represented by a complex system, which the target is the catalyst regeneration by partial burning of the coke deposited on the catalyst [3].

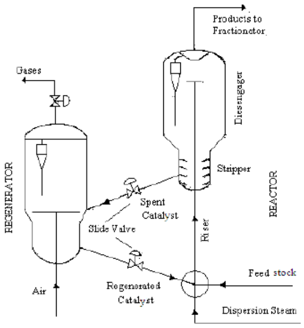

Fig. 1 Industrial fluid catalytic cracking unit [3]

VII. ADVANCED PROCESS CONTROL

Aspect of advanced control strategy or of intelligent control is to develop systems that incorporate the creative, abstract, and adaptive attributes of a human, while minimizing the undesirable aspects such as unpredictability, inconsistency, fatigue, subjectivity and temporal instability. Advanced or intelligent controllers are able to perform under significant process uncertainties and incompleteness in the system and its environment, being reconfigurable to scope automatically with system failures and sufficiently adaptive to cope with new goals or unanticipated situations. Advanced control strategies attempt to compensate for process deviations in the shortest possible time by accounting for process dynamics, dead times, time delays and loop interactions. The benefit of advanced control is:

- Increased throughput
- Increased product recovery
- Energy conservation
- Reduced disturbances to other processing unis
- Reduced operating manpower
- Increased plant flexibility.

Types of advanced process control strategies:

- Cascade control
- Predictive control
- Adaptive control
- Inferential control
- Statistical process control
- Intelligent control (artificial intelligence).

Why MBPC and MPC

The model predictive control (MPC) represent the open loop process response as vector. It is use in standard industrial practice and is marketed by many control consulting and DCS vendor companies. Several major petrochemical companies have developed in-house controllers.

Process models can be developed from a first-principle or phenomenological point of view, based on material and energy balances and thermodynamic relations. Design-type simulators are of this type of configuration. The MBPC model accounts for changes in process gain and dynamics, and once tuned, the controller does not need to be returned when the process conditions change. The same MBPC model can be used for supervisory economic process optimization throughput the process operating range. For nonlinear or non-stationary processes, the self-tuning, diagnostic and economic optimization advantages of MBPC can offset the engineering effort required to develop an appropriate phenomenological model [32].

Model based predictive control of FCCU

The model based predictive control is one of the advanced control method, which can manage these control problem efficiently. The predictive controller contains two major components: the model process and an optimal module. It is the main objective of the FCCU are to maximization of the yield of the gasoline. This desiderate is achieved if in the reactor take place a good conversion and in the regenerator is obtain a good combustion. The riser outlet temperature is use to control the conversion and the regenerator temperature is used to control the combustion.

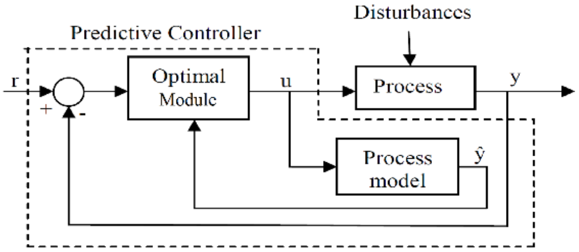

Fig. 2 MBPC structure.

A conceptual representation of the predictive control structure associated to the fluid catalytic cracking process presented in figure. The input variables of predictive controller are:

- Disturbance of the process (the feed stock temperature – $T_{mp,}$ regenerated catalyst temperature – $T_{reg\ 1,}$ feedstock flow – Q_{mp};
- The set point of the controller (optimal riser outlet temperature - T_r^i and optimal regenerator temperature – T_{reg}^i;
- The feedback variable of the process (riser outlet temperature – T_r and regenerator temperature – T_{reg}.

Regarding the manipulated variables of the controller, these are the regenerated catalyst flow – Q_{cat1} and air flow in the regenerator – Q_{air} [3,27].

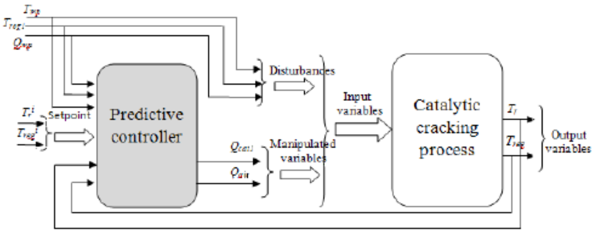

Fig. 3 The predictive control structure of the catalytic cracking process [3,27]

VIII. DISTRIBUTED CONTROL SYSTEM (DCS)

The distributed control system (DCS) is the dominant form of instrumentation used for the industrial process control. The dimensions such as distributed processing, distributed data and distributed control characterize the distributed control system. DCSs designed to satisfy the needs of continuous processes. The controllers based around the PID control algorithm with numerous supporting regulatory algorithms such as summers, multipliers, selectors. The early DCSs did not do a job of addressing the requirements for discrete and batch control applications. Since batch processes typically need regulatory, sequential, and discrete types of control, e.g. programmable logic controllers (PLC). The high-speed ladder logic of the PLC is usually performs independently of the functions being performed in the rest of the DCS. The integration of PLC into DCS has been limited to data exchange. DCS has evolved into a flexible and powerful integrated control system that supplies data acquisition, advanced process control, and batch control capabilities. In DCS, equipment is separated in functional areas and is installed in different work areas of a process plant. The plant operator monitors and manipulates the set-points of the process parameter from central control room. The operator views the process information transmitted from the processing area and displayed on the computer terminal and changes control conditions. The controlling portions of the DCS, distributed at various locations, performs the following two functions at each location:

- Measurement of analog variable and discrete (digital) inputs.
- Generations of output signals to actuators that can change process conditions.

A DCS consists of the following modules:

- Operator stations that use microprocessor-based computer terminal (CRT) displays and keyboard communication with control devices and displays
- Remote multi-function microprocessor-based controllers (PLCs)
- A digital data link (data highway) that connects the multi-function controllers with the central operator stations.

The first priority of DCS is to provide superior operator interfacing and real-time process control. The system architecture provides for distribution and connectivity of control devices and computing platforms throughout the plant. The flexibility of implementations of sequential control and integration among the various types of control is also additional strength of DCSs.

Feature of DCS

The DCS architecture provides a single window to the process and control systems so that it can perform the following function:

- Monitor and manipulate the process
- Retrieve historical data
- Configure the system
- Build schematic displays
- Develop control programs
- Diagnose system failures.

Advantages of DCS

The interface with the process is improved for the benefit of the operators: The group display provides a means of viewing a combination of control loops that has meaning in terms of process association. Configuration from the keyboard allows rearranging or adding to the display without the purchase and installation of new equipment.

They are more reliable, i.e. even if central station facilities breakdown the remote control operation will continue without interruption. It is flexible and relatively easy to expand. The programming required to tailor the system to the needs of the individuals process to which it is applied can be done without knowing a high-level programming language [33].

IX. CONCLUSION

In this review paper are presented aspects of propylene maximization via fluid catalytic cracking technology by the automation and control methodology through model based predictive control. The main constraints for maximized propylene yield are based on having a suitable catalyst suitable reactor configuration and reaction condition. The control system eliminates the effect of the distribution which appear in the process, the MBPC model accounts for the changes in process gain an dynamics and once tuned the controller does not need to be returned when the process conditions change. For non-liner process the self-tuning, diagnostic and economics optimization advantages of MBPC also DCS is very effective to automate as a control scheme.

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