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Effects of Reaction Temperature and Catalyst Type on Fluid Catalytic Cracking (FCC) of Crude Oil Feeds: A Microactivity Test Unit Study

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ABSTRACT

This study investigates the effects of reaction temperature and catalyst type on the fluidized catalytic cracking (FCC) of crude oil feeds in a micro-activity test (MAT) unit. It explores the variations in the reaction conditions that impact changes on product yields, specifically, the gas, liquid, and coke of the paraffinic feeds. A fixed-bed MAT setup featuring precise temperature settings and catalyst-to-oil (C/O) ratios is used. The experiment included gas chromatography, simulated distillation, and carbon analysis to analyze product production, composition, and yield. The results indicate that at higher temperatures and C/O, as opposed to thermal cracking, FCC employs a catalyst that cracks large hydrocarbons into smaller, valuable hydrocarbons. These ratios increased the overall conversion, and they also fostered the formation of olefins, such as propylene and ethylene. The results revealed the need to optimize the FCC parameters to balance conversion efficiency, product selectivity, and catalyst longevity while reducing coke formation and catalyst deactivation. This balance is a direct input for maximizing product value and efficiency in today's refineries.

Keywords: micro-activity test (MAT), fluid catalytic cracking (FCC), conversion efficiency, products' distribution, experimentation, catalyst longevity

1. INTRODUCTION

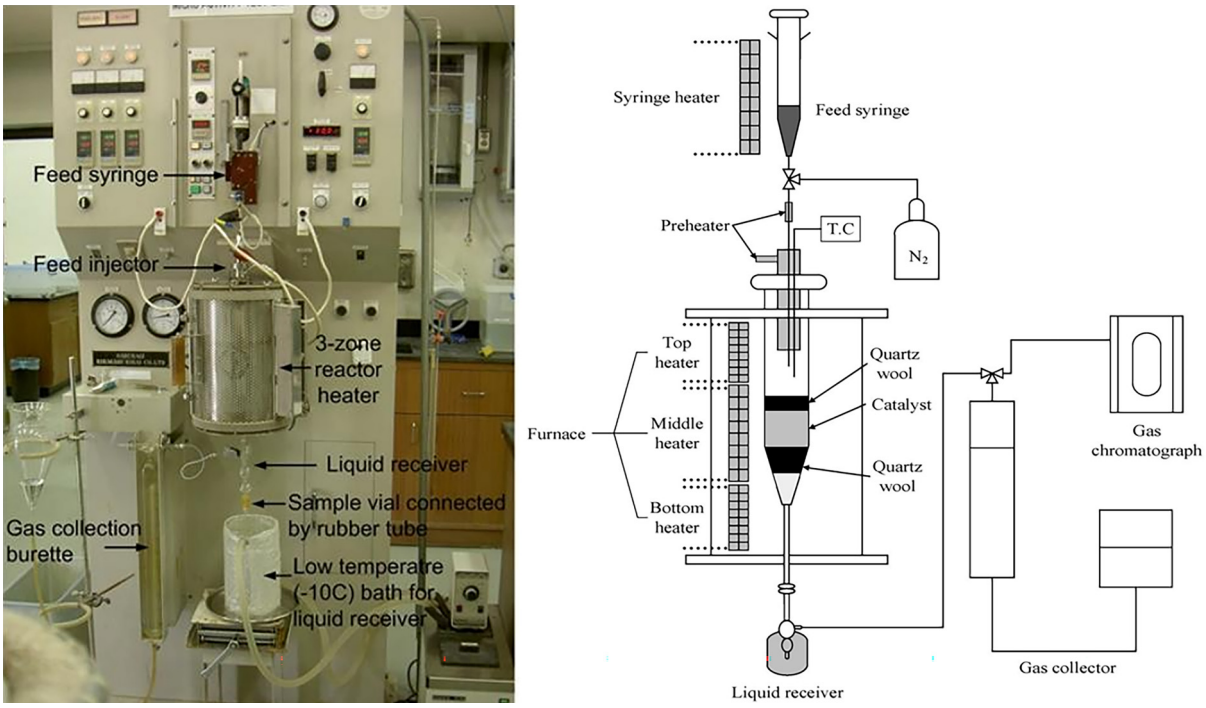
The transformation of crude oil into useful chemical products has been a major challenge for the petrochemical industry. Until now, crude-oil refining has primarily focused on gasoline and diesel production. However, the growing market for olefins, such as propylene and ethylene, has driven the development of new refining methods. One such approach—direct oil-to-light olefins—has led to significant market development.

Fluid catalytic cracking (FCC) is an essential technology instrumental to this transition. The share of FCC conversion process is approximately 16% of the total crude distillation capacity in oil refining worldwide. The initial objective of its development was to improve the production of gasoline from heavy oil. However, currently, FCC has become a widely adopted technology for refining all types of crude oil, such as gas oil and heavier residues, into higher value products [1–6]. The FCC process involves a powdered catalyst that becomes a fluid when added to hydrocarbons and then vaporizes it. In contrast to thermal cracking, FCC employs a catalyst to crack large hydrocarbons into small, valuable hydrocarbons, such as light olefins and aromatics, while also producing gases, liquid fuels, and coke as byproducts [7].

Several researchers have investigated the effect of temperature and catalytic properties on the FCC performance. Rahimi and Karimzadeh asserted that the reactor temperature was a conducive factor for conversion; however, it was associated with overcracking and coke formation [8]. Corma et al. explored the potential of zeolite-based catalysts and demonstrated that the catalyst acidity and pore size were key factors influencing product selectivity of the products [9]. Furthermore, Ancheyta et al. elaborated on the kinetics aspect and showed that the FCC process is conditioned by the type of feed used and the operation variables [10]. Microactivity test (MAT) units, as evaluated by Bjørgen et al., further verify catalyst activity and the positive effect that the supported materials and regeneration have in a lab-scale setup [11].

At King Fahd University of Petroleum and Minerals (KFUPM) Center for Refining & Advanced Chemicals, various reaction conditions on the performance of the FCC process were investigated with a MAT unit. The MAT unit is a suitable instrument for testing the products of FCC catalysts through a method in which the user controls the reaction on a small scale and has parameters such as temperature, pressure, and catalyst/oil (C/O) ratio finely tuned [12]. The FCC tests in this study utilize the standard procedure of placing the catalyst in the bed of the reactor, injecting a measured amount of crude oil, and heating using a syringe pump. As the crude feed contacts the catalyst, it cracks into gaseous, liquid, and solid products, which are directed into separate containers for quantification and conversion efficiency analysis.

Numerous studies have explored the optimization of the FCC for model feedstocks or under generalized catalytic conditions. However, few studies have systematically investigated the combined impact of temperature and catalyst type on crude oils with different compositions. This study evaluates FCC performance of light crude oil feeds such as Arabian Extra Light (AXL) using



(a) Physical MAT Components (b) Flow Diagram of MAT

Figure 1. MAT unit components and its schematic [15,16]

different catalyst systems under controlled MAT conditions. This approach evaluates the impact of feed properties and catalyst characteristics on product distribution and coke deposition.

2. METHODOLOGY

2.1. MAT Unit. A fixed-bed MAT unit was employed to test catalyst with light feedstocks, using a quartz or stainless-steel tubular reactor (22 mm inner diameter and 380 mm in length). Figure 1 shows a the layout of the MAT setup and its components. An identical bench-scale reactor was used to experimentally examine the naphtha cracker feed. However, instead of standard iced water cooling, a low-temperature chiller that was kept at −10 °C was directly connected to the reactor jacket to chill the incoming feed. The −10 °C quenching temperature, emphasized by Altamira Instruments [13], was selected to rapidly condense volatile products, minimizing light component loss and ensuring accurate mass balance and yield analysis. This adjustment ensured more stable temperature control throughout the reaction. The receiving system was also modified to accommodate high product volatility. A wide-mouth 2 mL sample vial capped with a tightly fitting rubber hose was held at the bottom of the receiver to ensure a sealed, gas-tight connection of the two parts of the system to minimize losses and prevent contamination.

A 30 s reaction time was used in each experiment with the MAT unit. This aligns with the American Society for Testing & Materials Test Method ASTM D5154M-25 [14], which recommends short contact times to simulate FCC riser conditions and prevent excessive secondary cracking. The test commenced by first adding a fixed amount of the catalyst to the reactor. Subsequently, the system was flushed with nitrogen gas for 15 min before the feed was introduced. Once the liquid receiver and gas collection system were set up and the liquid receiver was cooled for the gas products to condense, a leak test was performed before the experiment began. The reactor was filled with 0.9 g of crude oil for 30 s. At the end of the reaction, the catalysts were stripped from hydrocarbons using nitrogen for 5 min.

The product gas was collected in a burette and analyzed using a gas chromatograph, and the liquid products were analyzed via simulated distillation. The exact amount of feed oil was measured from the weight difference of the feed micro-syringe before and after the MAT run. Table 1 presents the operating conditions of the MAT unit. The data obtained were compiled into an Excel sheet for further interpretation.

2.2. Analysis of Gas, Liquid Products, and Coke . The cracked output comprises gaseous products, liquid hydrocarbons, and solid coke. To assess the feedstock performance, a comprehensive gas chromatographic analysis was conducted on the products obtained from the MAT unit, providing detailed yield distributions.

2.2.1. Analysis of gaseous products. Gaseous components were analyzed using a Fusion® Inficon MicroGC unit having three thermal conductivity detectors , enabling precise quantification of light hydrocarbons up to C4, including C5 paraffins, hydrogen, and fixed gases. This system offers a rapid analysis with high sensitivity, making it suitable for refinery gas applications. The analysis accurately measured hydrocarbons ranging from C1 to C4 and C5 paraffins. The masses of each identified gas component were summed, and the masses of compounds heavier than C4 were combined with the liquid product weight to determine the overall product distribution. Comparative studies have demonstrated the effectiveness of such analytical approaches for

Table 1. *Operating conditions of the MAT.*

Activity	Operating Conditions
Injected feed weight	1 gram
Weight of catalyst weight	A multiple of the catalyst weight to achieve the required C/O ratio
Time-on-stream (time of feed injection)	30 s
Temperature of feed syringe	60 °C
Temperature of feed injector	5 °C higher than reaction temperature
Temperature of liquid receiver	-9 °C
Liquid/catalyst stripping time with receiver in cold bath with cold bath removed	Total 8 min 5 min 3 min

evaluating FCC product yields across different reactor configurations [17].

2.2.2. Analysis of liquid products. Unlike conventional physical distillation methods, gas chromatography with a flame ionization detector (FID) was used to simulate the distillation of the cracked liquid product, providing a rapid and precise analysis of boiling point distributions in petroleum fractions [18]. The liquid products contained three different fractions, namely, gasoline of naphtha (C_5-221 °C), heavy cycle oil (343+°C) and light cycle oil (221–343 °C).

2.2.3. Analysis of solid coke product. The amount of coke deposited on catalyst after the MAT run was examined using a Horiba carbon analyzer (Model EMIA-220V). One gram of the spent catalyst (with tungsten added as a combustion promoter) was combusted in a furnace at elevated temperature, at approximately 760 °C. The CO_2 resulting from the combustion was passed through an infrared analyzer, and the amount of carbon was estimated (as a percentage of catalyst weight).

Figure 2 shows the conventional FCC schematic and catalyst processes used for the analysis of the gas and liquid products and coke operations.

3. EXPERIMENT

The distillation and physical properties of crude oil feeds (AXL, AL, and AH) are shown in Table 2. For AXL, the simulated distillation results showed 40% gasoline, 26% middle distillate, and 33% heavy oil. Per structured multiphase guidelines, the experiment for catalyst optimization in the FCC unit was performed. First, a trial run was implemented with the present FCC catalyst for comparison to improve the operation and understand the bottlenecks of the unit. The choice of the catalyst was the first step in the physical and chemical analyses, followed by steam deactivation to reach the equilibrium state.

Tests in the MAT unit were performed by adjusting the steaming conditions and C/O ratios. Subsequently, the results were analyzed and screened using a kinetic model to establish a definitive economic practicality. Using the results of evaluating economics, the best-known solution was established, qualitative analysis was conducted, and references were checked. The post-choice comprised monitoring the change following a test run, ensuring that the correct computer model was in action, and collecting vital signs. Finally, a report was created that required knowledge of changes in performance and the impact of methodological measures.

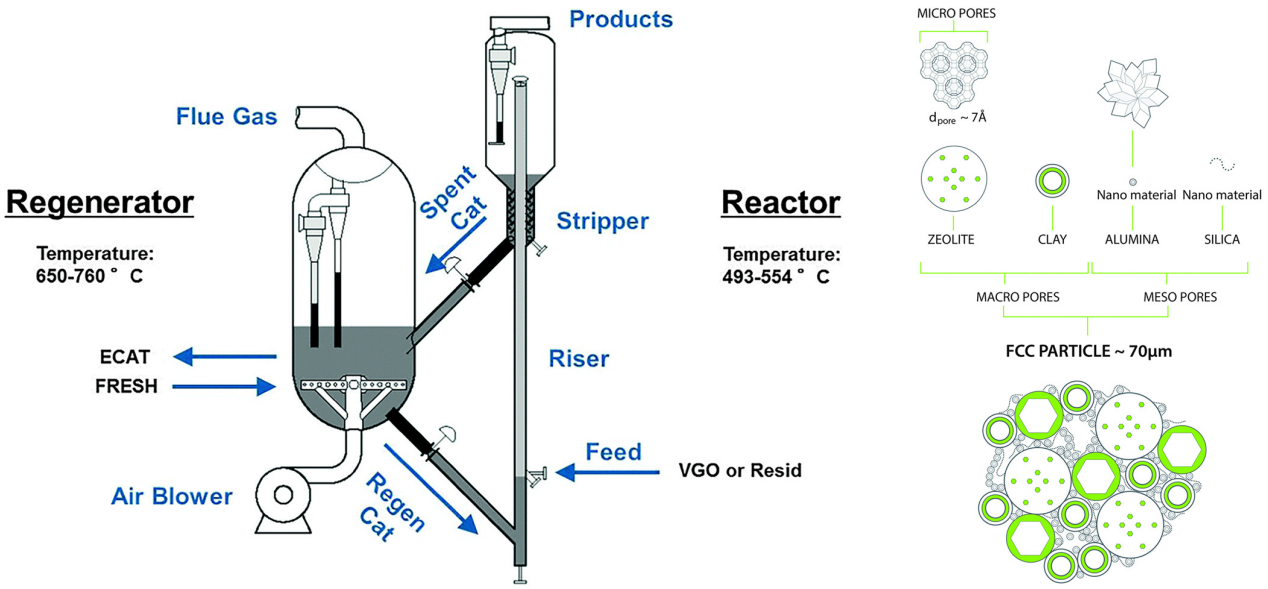


Figure 2. Conventional FCC Schematic and catalyst processes [12]

Table 2. *Physical and distillation properties of crude oil feeds.*

Property	AXL	AL	AH
API Gravity (degree)	39	34	21
Sulfur (wt. %)	1.6	2.3	2.9
Vanadium (ppm)	2.7	16	30
Nickel (ppm)	<1	3.3	9
Elemental composition (wt. %)			
Carbon	84.3	84.3	–
Hydrogen	12.6	12.2	–
Nitrogen	0.7	0.64	0.15
Simulated distillation-SimDist (°C)			
Initial boiling point	25	22	22
50%	287	307	350
Final boiling point	577	580	590
Distillation fractions (wt. %)			
Gasoline (C_5–221 °C)	41	35	20
Middle distillates (221–343 °C)	26	26	22
Heavy oil (343 °C+)	33	39	58

The general cracking reaction mechanism depends on the intrinsic zeolite acidic characteristics of the catalyst. The high-acidic and wide mesopores of the FCC catalyst facilitated the cracking of large hydrocarbon molecules (heavy oil) to light fractions, mainly light olefins and aromatics. The deposition of coke was more related to thermal and not catalytic cracking with the increase in temperature. The MAT tests provided catalytic activity and selectivity curves, which mean yield curves depending on conversion, defined as the sum of coke and total gas yields.

4. RESULTS AND DISCUSSION

Following the experimental procedures, the obtained data were compiled using Microsoft Excel for visualization and detailed analysis. The results were used to demonstrate the influence of different temperatures and catalyst parameters on the FCC performance of several crude oil feeds. The evaluation focused on determining significant trends, recognizing unexpected trends, and comparing results with the existing literature. This section discusses the efficiency of conversion, distribution of the product (vapor, liquid, and coke), and performance of the catalyst. These factors provide valuable information for identifying the most efficient method for increasing yield while minimizing byproducts.

4.1. Effects of Temperature and Catalyst Observed.

The experimental results showed that the FCC process is highly dependent on temperature and catalyst characteristics. The rise in temperature improves thermal cracking and catalytic activity, thereby enabling β-scission reactions that are in accordance with

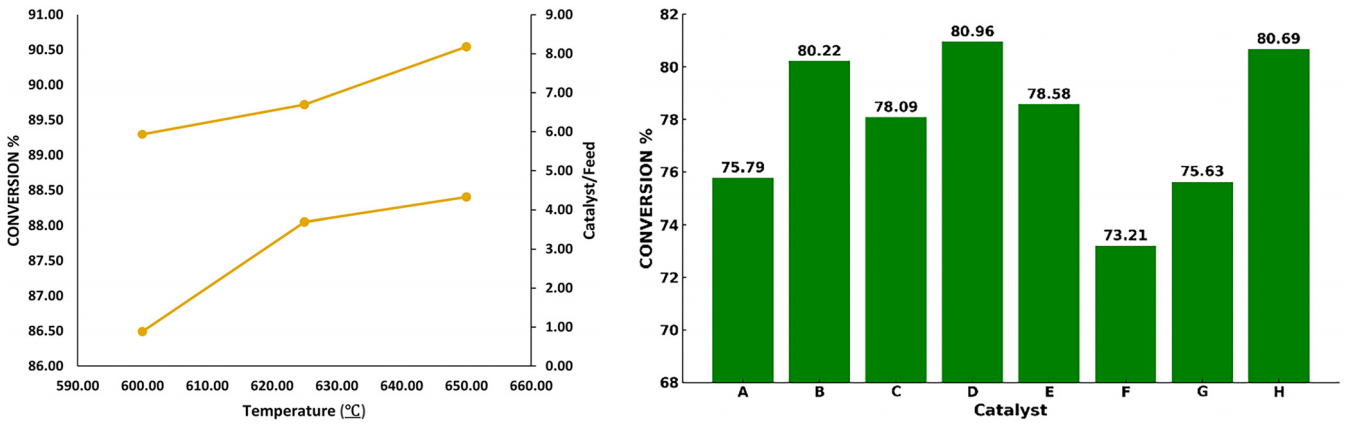


Figure 3. Effect of temperature and catalyst on overall conversion: (a) Conversion percentage of AXL with respect to temperature and C/O ratio; (b) Effects of different catalysts on the conversion percentage of AXL feed at 650 °C

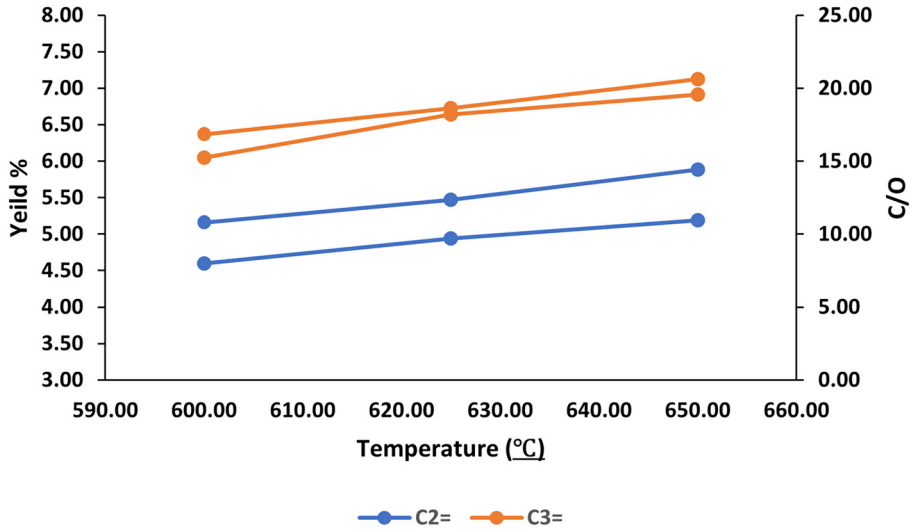


Figure 4. Yield percentage of C2 and C3 from AXL Feed and Catalyst with respect to temperature and C/O ratio

the formation of short-chain olefins, such as propylene and ethylene. Conversely, high temperatures lead to the over-cracking of intermediates, such as gasoline-range hydrocarbons, resulting in less liquid and more gas. This aligns with the endothermic characteristics of olefin synthesis and the thermodynamic compatibility of the gas-phase products at elevated temperatures.

Generally, an increase in both the temperature and C/O quotient is favorable for crude feed conversion. However, high values can spur overcracking, which can reduce the formation of usable products, such as gasoline, and increase light gas production. Gas products such as ethylene and propylene showed only a slight increase in their yields, indicating that only a small amount of gas was generated under the FCC standard conditions.

Liquid yields, particularly of gasoline, showed a more significant response and declined when the conditions were above the optimum level. Additionally, heavier and more aromatic feedstocks increased coke formation, particularly as temperature and catalyst activity were considered. Therefore, controlled and stable catalysts must be developed to achieve satisfactory results. Consequently, maximizing temperature and catalyst parameters in FCC operations helps maintain process efficiency, product selectivity, and catalyst stability.

4.1.1. Effects of temperature and catalyst on overall conversion. The overall conversion obtained from FCC of the oil feed is related to the temperature and amount of catalyst. Theoretically, increasing the temperature and C/O ratio would increase the overall conversion of the crude feed in the FCC. Figure 3(a) shows a 2% increase in the overall conversion with increasing the temperature by 50 °C and the amount of catalyst by 3 in the FCC of AXL oil feed. This indicates the significant impact of temperature and catalyst amount on the overall conversion of the crude feed in FCC. As the type of catalyst is essential for overall conversion, it must be carefully selected. Figure 3(b) shows the effect of different catalyst types on the AXL oil feed conversion under identical conditions. Catalysts

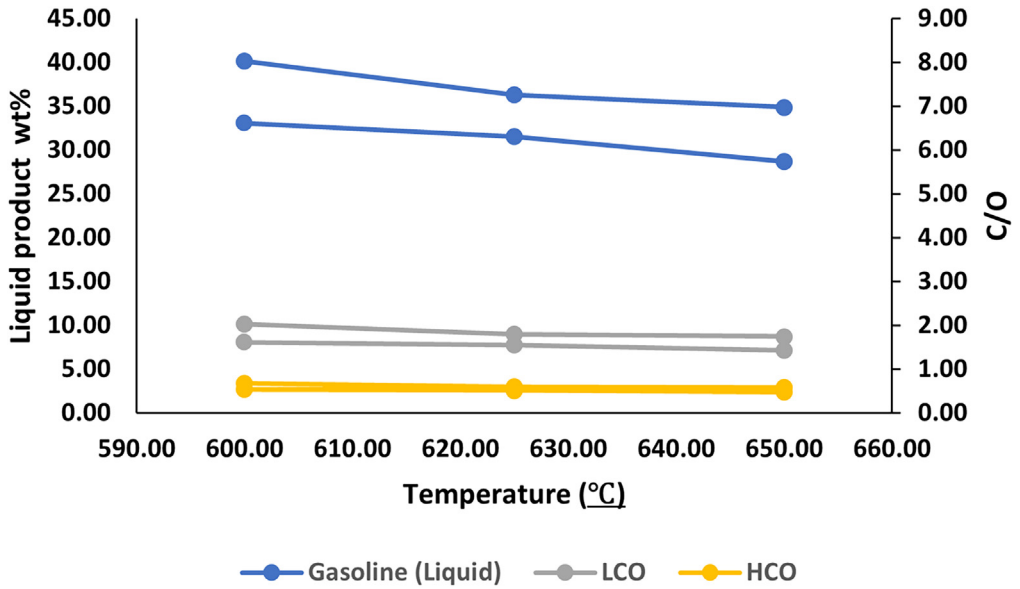


Figure 5. Amount of liquid products in wt% from AXL feed with catalyst with respect to temperature and C/O ratio

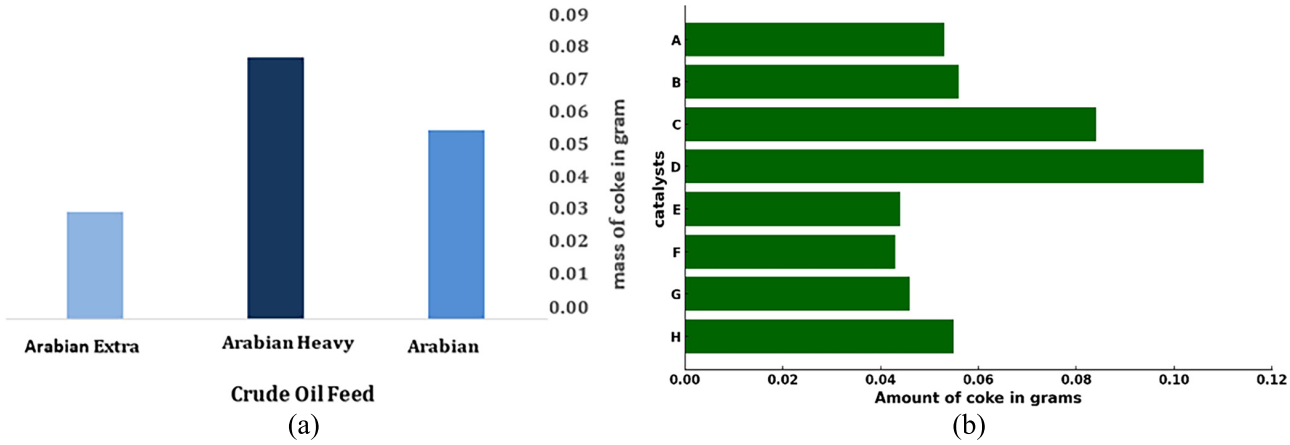


Figure 6. Effect of temperature and catalyst on coke: (a) Amount of coke in grams produced by different types of crude feeds; (b) Effect of different catalysts on the amount of coke produced from the FCC of AXL crude oil at 530 °C and 7 C/O ratio

A–H are proprietary formulations with undisclosed compositions, evaluated through a screening approach.

4.1.2. Effects of temperature and catalyst on gas products yield. Ethylene (C2=) and propylene (C3=) gases are two of the main products obtained from the FCC process and are essential in the production of various plastics and petrochemical products; their yields are also influenced by the temperature and catalyst amount. Additionally, optimizing these parameters can increase the efficiency and profitability of the production process. As shown in Figure 4, increasing the temperature by 50 °C and C/O by 1 would increase the yields of propylene and ethylene by 0.63% and 1%, respectively. This indicates the minor effects of the variables on the gas products because the FCC produces lower gas yields than liquid products and requires extremely high temperatures to overcome gas product condensation.

4.1.3. Effects of temperature and catalyst on liquid products yield. FCC generates three main types of liquid products: gasoline, low-boiling point light cycle oil (LCO), and high-boiling-point heavy cycle oil (HCO). Gasoline is particularly valuable, and most FCC units aim to maximize the conversion of their feeds to fuels and other liquefied petroleum gas (LPG). The increase in temperature and C/O ratio has a more significant impact on liquid products, such as gasoline, LCO, and HCO, compared to gaseous products, such as ethylene and propylene. FCC produces significant amounts of gasoline and other distillates. However, excessive conversion may reduce gasoline yield and increase LPG generation[19,20]. Thus, the gasoline yield has an inverse relationship with temperature and C/O; reducing the temperature would increase the gasoline yield (Figure 5).

4.1.4. Effects of temperature and catalyst on coke. The FCC process produces a solid product known as coke, which is combusted to CO_2 during the regeneration cycle, and the heat generated is used to heat the catalyst and feed undesirable byproducts of the condensation of hydrocarbon vapors on catalyst surface during cracking. This deactivates the catalyst and reduces efficiency. To restore activity, coke is burned off the catalyst through regeneration. These observations indicate that feedstocks with higher boiling points and greater aromaticity, such as crude feed, yield larger amounts of coke[21]. This relationship is exemplified in Figure 6(a), which shows that AH produces a higher amount of coke than AL or AXL crude oil feeds. This is because heavier feeds such as AH have larger quantities of polyaromatic hydrocarbons and compounds with high boiling temperatures, which are more susceptible to polycondensation and carbon deposition. These components are resistant to catalytic cracking and form refractory species that generate coke upon decomposition. Additionally, the elevated metal and asphaltene contents in AH contribute to catalyst fouling and further accelerate coke formation during cracking.

As shown in Figure 6(b), catalyst D produces the highest coke yield for the AXL crude feed due to its higher conversion. As conversion depends on both temperature and C/O ratio, coke formation also correlates with these parameters. This relationship aligns with recent studies showing that increased C/O ratios enhance conversion and coke yield, as greater catalyst availability promotes secondary cracking and condensation reactions that deposit carbonaceous species on the catalyst surface. Specifically, at C/O ratios between 1 and 7 and temperatures of 510–550 °C, coke yields increased sharply from 1.3% to 6.3% in parallel with conversion gains[22]. Thus, the FCC conditions require balancing the desired conversion with manageable coke levels, guided by C/O and operating temperature strategies.

5. CONCLUSIONS

This study explored the impact of various process conditions , such as reaction temperature, catalyst type, and crude oil feed, on the performance of FCC using crude oil feeds. It analyzed product yields, namely gas, liquid, and coke, under set-up conditions to identify the most suitable conversion routes. Based on the results of MAT experiments, the following conclusions were drawn:

- High temperatures and C/O ratios lead to faster conversion rates and light olefin (C2=, C3=) formation.
- The gasoline yield is highest at moderate temperatures and catalyst conditions, whereas extremely high values cause overcracking, and LPG becomes the dominant component.
- Coke formation mostly occurs during feed conversion, primarily for heavier feedstocks, such as AH crude.

- The choice of catalyst type has the most significant effect on oil conversion and coke deposition , indicating the crucial role of tailored catalyst use.
- Pretreatment methods such as hydrotreating and demetallization are crucial for reducing catalyst deactivation and coke formation, thereby improving the overall process efficiency.

The results align with current attempts to improve FCC operations and produce both fuels and chemicals. Catalyst selection can be performed through formulations that limit coke precursors, particularly if the feed is heavy. Future studies may validate these results at pilot and industrial scales, examining the effects of different feed pretreatment methods (such as hydroprocessing) and testing the efficiency of catalyst regeneration for high coke loads.

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CONFLICTS OF INTEREST

The authors report no conflicts of interest.

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