

The Use of Gas-to-Liquid Technology (GTL) to Produce Gasoline and Diesel Fuels

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ABSTRACT

The conversion of methane gas to synthesis gas (CO and H₂) and then into clean liquid fuels via Fischer–Tropsch synthesis is investigated in the present work. The effects of the catalyst type, pretreatment conditions, and process temperature on the catalysts activity and selectivity are investigated.

The syngas production and Fischer–Tropsch synthesis were carried out in two catalytic units connected in series. The first one contains a fixed bed reactor of 128 cm³, while the second fixed bed reactor is of 68 cm³. The results of syngas production over the prepared (Pt/HY) catalyst showed excellent resistance to carbon deposition and stable performance during 20 h-on-stream at 700°C.

The Fischer–Tropsch synthesis was carried out under different temperatures of 220, 230, 240, 250, 260, and 270°C and constant atmospheric pressure. The results showed that the catalytic synthesis leads to a wide variety of products such as gasoline, diesel and waxes. It was concluded that the best operating temperature for all Fischer–Tropsch synthesis is 240°C, where, this temperature gives the highest hydrocarbons production for diesel and gasoline.

The results indicate that the Cu-Co/Al₂O₃ was the most active and selective catalyst in the Fischer–Tropsch process which gives the excellent production of the desired products.

In addition, this process shows a great potential for economical production of GTL fuels in Iraq at low costs.

Keywords: GTL technology; Fischer–Tropsch synthesis; catalysts preparation;

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Gasoline and diesel.

استخدام تكنولوجيا تحويل الغاز الى سائل لانتاج الكايزولين وقود الديزل

الخلاصة

تم في هذا العمل دراسة تحويل غاز الميثان الى الغازات الخلاقة (الهيدروجين و اول اوكسيد الكربون) وبعدها الى وقود سائل نظيف خلال عملية الفشرتروبش حيث تم دراسة تأثير نوع العامل المساعد وظروف المعالجات الاولية ودرجة الحرارة على فعالية العامل المساعد ونوعيته. انتاج الغازات الخلاقة وعملية الفشرتروبش تم اجراءها في وحدتين تحويلان على عامل مساعد مرتبطين على التوالي. الاولى تحوي على مفاعل ذو الحشوة الثابتة ذو حجم ٢٨ سم³ والاخر ذو حجم ٦٨ سم³. ان الغازات (المحضر اضهرت مقاومة عالية لتفكك الكربون وسلوك ثابت خلال ٢٠ ساعة تحت درجة حرارة Pt/Hy الناتجة ٧٠٠ درجة مئوية. عملية الفشرتروبش تم اجرائها تحت درجات حرارية مختلفة ٢٢٠ و ٢٣٠ و ٢٤٠ و ٢٥٠ و ٢٦٠ و ٢٧٠ درجة حرارية وضغط جوي ثابت. اضهرت النتائج ان العامل المساعد المستخدم اعطى انواع متعددة من النواتج مثل الكايزولين والديزل والشمع. وكانت افضل درجة حرارية للتشغيل هي ٢٤٠ درجة مئوية والتي اعطت اعلى انتاجية من الديزل والكايزولين. هو اكثر العوامل المساعدة فعالية في عملية الفشرتروبش Cu-Co/Al₂O₃ اشارت النتائج ان العامل المساعد والذي اعطى انتاجية رائعة من النواتج المرغوبة. اضافة الى ذلك العملية المستخدمة اعطت مخزون عالي للاقتصاد بانتاج وقود (الغاز الى سائل) في العراق بكلفة قليلة.

INTRODUCTION

In recent years, many changes have been introduced in petroleum industry through developing of a new process to produce clean fuels. These changes lead to improvement in the engine fuel economy and power output, reductions in the combustion noise and, more recently, in pollutant emissions of CO₂, CO, NO_x and particulate matter. The interest in improving the environmental protection and to promote the efficiency of the automotive motors encourages the formulation of new catalysts or development of new processes for gasoline and diesel production. Gas-to-Liquid (GTL) is one of the most effective and economic technology used to produce of liquid hydrocarbons from natural gas [1, 2, 3].

In general, the GTL technology consists of three main processes: synthesis gas (syngas) manufacturing, Fischer-Tropsch synthesis and product upgrading. Synthesis gas is a mixture of CO and H₂, which can be obtained from any carbon containing feedstock, such as natural gas. The main process for syngas production is catalytic partial oxidation of methane [2, 4]:



On the other hand, the Fischer-Tropsch reaction represents the heart of GTL process, because it determines the product type and distributions. The highly

exothermic Fischer-Tropsch reaction converts synthesis gas into a large range of linear hydrocarbons including gasoline, diesel and wax according to the following equation [5, 6, 7].



The most common Fischer-Tropsch catalysts are group VIII metals (Co, Ru, and Fe). Iron catalysts are commonly used, because of their low costs in comparison to other active metals. On the other hand cobalt catalysts give the highest yields and longest life-time and produce predominantly linear alkanes. Metal catalysts are usually supported on alumina, silica, and zeolite [1, 8, 9].

Many authors [3, 4, 8] pointed to the fact that, the design and operation of GTL process is very difficult, principally because the complex chemical reactions kinetics, so that numerous investigators have studied the the process experimentally and prepared a wide range of hydrocarbons by using different types of catalysts [5, 8, 9, 10]. Some have focused on Fe-based catalysts due to their interesting activity and selectivity towards hydrocarbons, while few of them have focused on modification of Co-based catalysts [2, 6].

Borg [11] showed that cobalt catalyst deactivate rather more rapidly than other types of catalysts (Fe based catalysts) on addition of significant amounts of water to the reaction feed. The effect is more pronounced with smaller cobalt particles. Chen et al. [12] reported that the addition of ZrO_2 decreases the adsorption intensity of CO, whereas it increases the amount of CO adsorbed on Co-based catalysts, which inhibits CH_4 formation and increased the selectivity for heavy hydrocarbons. Borg et al. [13] studied the Fischer-Tropsch synthesis and they found a clear, positive correlation between the Al_2O_3 catalyst pore diameter and the C_5+ selectivity. The same trend was found for mesoporous silica supported cobalt catalysts. Kiss et al. [14] studied hydrothermal deactivation of silica-supported cobalt catalysts. They demonstrated that high partial pressure of water results in the formation of a phase containing mixed oxides of support and cobalt which is inactive for the synthesis.

Most of the studies performed in the GTL technology have focused on the modification of syngas reaction and only a rather limited number of papers have focused on studying the influence of reaction conditions and the type of catalysts on the activity and selectivity in the Fischer-Tropsch reaction [10–16]. It is important to mention here that the development of Fischer-Tropsch catalysts will improve the production and selectivity of the process toward the desired hydrocarbons. On the other hand GTL technology has not been applied in Iraq yet, and it is known that Iraq has large quantities of natural gas reserves. Therefore, the main objectives of the present work are:

- 1-Prepare and modify more active, selective and stable catalysts for Fischer-Tropsch reactions.
- 2-Study the effect of the main process variables on the catalyst activity and selectivity through a wide range of operation conditions.

EXPERIMENTAL

- Feedstock

Iraqi methane gas (98.4% purity) delivered by Al-Basra Refinery (South Refining Company) was used as a feedstock in the present investigation. Hydrogen gas (99.99%), Oxygen gas (99.8%) and Nitrogen gas (98.9%) were supplied from Al-Mansour plant (Baghdad).

- Chemicals

Potassium Nitrate (KNO_3 , 99.97%), Cobalt Nitrate [$\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$], Copper Nitrate $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$, NaY-zeolite with (Si/Al) ratio of 2.6 and with extrudate shape of average size of 2x3mm, Alumina Al_2O_3 with spherical shape and average size of 3mm (FLUKA AG company), Hexachloroplatonic Acid H_2PtCl_6 (40% wt Pt, Riedel De Haen AG), and Ammonium Chloride NH_4Cl (BDH) are used in this work.

- Preparation of Pt/HY Catalyst

Pt/HY zeolite was prepared in order to be used as catalyst in syngas reactor. The Na^+ ions in NaY zeolite were exchanged for NH_4^+ ions to obtain the HY form by ion exchanging the original NaY zeolite with (3 N) ammonium chloride solution [12, 13]. The exchanged zeolite HY (86% Na^+ exchange) was loaded with Pt at concentrations of 0.5 wt % by impregnation process with aqueous solution of hexachloroplatonic acid H_2PtCl_6 . The prepared solution was added dropwise to the zeolite with mixing for 4 hours at 25 °C. The mixture was then left at room temperature for 24 hours, it was stirred intermediately during this time. The mixture was then slowly evaporated to dryness over a period of 8 hours at temperature of 75°C. The resulting catalysts were dried in air at 110°C for 10 hours, then, the samples were calcined in air at 550°C for 6 hours (increasing to that temperature at a rate of 0.5°C/min) and finally reduced to 400°C in flowing H_2 for 4 hours. Then, the sample are referred to as Pt/HY catalyst and used in syngas reactor.

- Preparation of Fischer-Tropsch Catalysts

For the operation of the second catalytic unit of Fischer-Tropsch reactions, three types of catalysts were prepared: monometallic 15%Co/ Al_2O_3 , and promoted 0.02%K-15%Co/ Al_2O_3 , and 0.05%Cu-15%Co/ Al_2O_3 catalysts were prepared by incipient-wetness impregnation method.

Co/ Al_2O_3 Catalyst

The Co/ Al_2O_3 catalyst was prepared by incipient-wetness impregnation [2, 14]. The support Al_2O_3 was first calcined at 600°C for 6 h. Cobalt nitrate [$\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$] was dissolved in deionized water and impregnated into the support using two-steps incipient wetness to produce a final catalyst with 15 wt% cobalt. Thus, 10 g of [$\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$] was dissolved in 47 ml of distilled water. Then the solution was added to 20 gm of the alumina sample as dropwise. Impregnation was carried out at 25°C for 3 h under constant stirring. After each impregnation, the catalyst was dried in an oven at 110°C, for 24 h. After the last impregnation and drying, the catalyst was calcined in flowing dry air, at 400 °C, for 5 h, using a heating rate of 5 °C/min.

POTASSIUM PROMOTED CATALYST

The promoted K-Co/ Al_2O_3 catalyst was prepared by incipient-wetness impregnation method. Thus, 10 g of [$\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$] and 3 g of KNO_3 were dissolved in 47 ml of distilled water. Then the solution was added to 20 gm of the alumina sample as drop wise. Impregnation was carried out at 25°C for 3 h under constant stirring. Impregnated catalyst was dried in an oven at 110°C, for 24 h. The dried catalyst was calcined in flowing dry air, at 400 °C, for 5 h, using a heating rate

of 5 C° /min. Then, the potassium promoted catalyst was called as 0.02% K - 15%Co/Al₂O₃ catalyst.

COPPER PROMOTED CATALYST

The promoted Cu-Co/Al₂O₃ catalyst was prepared by dissolving a 10 g of [Co(NO₃)₂.6H₂O] and 10 g of Cu(NO₃)₂.3H₂O in 60 ml of distilled water. Then the solution was added to 20 gm of the alumina sample as dropwise. Impregnation was carried out at 25C° for 3 h under constant stirring. Impregnated catalysts were dried in an oven at 110C°, for 24 h. The dried catalysts were calcined in flowing dry air, at 400 C°, for 5 h, using a heating rate of 5 C° min⁻¹. At this stage the copper promoted catalyst was called as 0.05% Cu -15%Co/Al₂O₃ catalyst.

FISCHER-TROPSCH REACTIONS TEST

Fischer–Tropsch reaction was performed in the second catalytic unit. The fixed bed reactor dimensions were 20 mm ID, 30 mm OD and 210 mm height with reactor volume of 66 cm³. The reactor was heated uniformly using an electrical furnace. The temperature inside the catalyst bed was controlled through using of a thermocouple sensor type K. The reactor was fitted with accurate means for control of pressure, and gas and liquid flow rates. The experiments were conducted at atmospheric pressure. The syngas feed (CO/H₂) was kept at constant ratio of 2 using hydrogen gas cylinder connected to the system. The temperature of syngas feed was controlled by using refrigeration system.

For each experiment 20 gm of catalyst was charged into the reactor. Before each run, the catalyst was dried at 110 °C in nitrogen flow for one hour and then reduced at 300 C° in hydrogen flow for three hours. The reaction conditions were as follows: space velocity (GHSV) of 1800 ml g⁻¹ h⁻¹, atmospheric pressure and reaction temperature was varied between 220 and 270 C°.

The effluent from the reactor contains un-reacted CO and hydrogen, as well as low and high molecular weight hydrocarbons. The G.C. analysis was used to obtain product distribution. The peak areas for the reactants and products were normalized by an external standard. All of the collected data were obtained after at least 1 h on stream of reaction to ensure steady-state conditions. The basis for the selectivity calculation was the number of moles of carbon present in a given product and the total number of moles of CO converted. Then, the calculations included the selectivity of CH₄, gasoline cut (C₄–C₁₂), diesel cut (C₁₃–C₂₁), and others of high molecular weight like waxes(C₂₂⁺), and CO conversion.

- Catalysts Characterization

X-Ray diffraction analysis was carried out using Phillips X" Pert Pro PW 3719 X-ray diffractometer with Cu K α 1 and Cu K α 2 radiation source (λ =1.54056 Å and 1.54439 Å) respectively. Slits width 1/8 and 1/4 have been applied. (Tension=40 kV, Current=30 mA). The range of angles scanned was (20 to 70) on 2 θ .

On the other hand, the catalysts surface areas and pore volume were determined using (BET) method, the apparatus used was Micromeritics ASAP 2400 located in Petroleum Research Center / Ministry of Oil (Baghdad).

-Process Description

Figure (1) shows a view of the synthesis and Fischer Tropsch unit while figure (2) shows a schematic diagram of the GTL process and all parts of them are labeled in

this figure. The GTL process apparatus consists of two catalytic units connected in series. This system was constructed at the Chemical Engineering Department/University of Technology. The first unit was specified for syngas production and the second one for the Fischer-Tropsch reactions.

In industry and academic research many processes are applied to produce syngas (CO and H₂). The main two processes are steam reforming of methane, and partial oxidation of methane [5, 13]. In the present work partial oxidation of methane is used to be the source of CO and H₂ generation. Then, CO and H₂ are used in the second process reactor of Fischer-Tropsch.

Syngas unit consists of a vertical tubular stainless steel reactor of 20 mm internal diameter, 30 mm external diameter and 680 mm height (reactor volume 214 cm³). The reactor is heated uniformly using an electrical furnace. The temperature at the reactor center of the catalyst bed is controlled by a thermocouple sensor type K (iron-constantan). The reactor is fitted with accurate means for control of pressure, gas and liquid flow rates. The experiments were conducted at atmospheric pressure. Flows of methane and oxygen into the reactor were adjusted to the desired ratio of methane to oxygen [3, 12]. Gases mixture was preheated to reactor temperature before entering the bed.

In the first reactor a 50 gm of Pt/HY catalyst was used. Before each run, the catalyst was dried at 110 C° in nitrogen flow for one hour and then reduced at 400 C° in hydrogen flow for three hours. The operating conditions for syngas production were selected to give the highest conversion of CO depending on many factors given in the literature on Pt/HY catalyst. The temperature was selected to be 700C° and the operating pressure was held constant at 1 bar [7, 11]. The methane gas flow rate was 25 L/hr. Samples of syngas products were produced in the first reactor and were analyzed in a gas chromatograph (Shimadzu GC-2014) FID and TCD by using capillary column (S.G.E., length=25 mm, I.D.= 0.22 mm, film=0.2μm) and using N₂ as a carrier gas.

The fluidized bed column was constructed of (0.1 m) diameter glass column with a height of (1m). The distributor was a perforated plate made of aluminum sheet of 0.003m thickness with about 1.2% fraction free area (14). Air from a laboratory compressor was used as the fluidizing gas. Fluidizing air was regulated with two rotameters before the perforated plate distributor. Three types of sand particle diameter were used in the fluidizing bed, 205, 424 and 775 μm (using the geometric mean particle diameter, narrow cut solids) at group B of Geldart classification. The physical properties are listed in Table(1).

Two quantities (8.5 kg and 9.5kg) of sand particles were charged into the bed to give a static bed height of about (30 cm) and (40 cm) respectively.

Air was introduced from the air bottom to the column flows upward.

The bed was first fluidized and allowed to settle. Later for various flow rate of air, the height of fluidized bed and pressure drop were measured across the bed by means of a manometer. The flow rate of air was measured using a rotameter.

The un baffled condition was also investigated, where before the baffle modules was introduced into the bed and the system was allowed to reach a steady state.

RESULT AND DISCUSSION

The properties of prepared catalysts (Pt/HY, Co/Al₂O₃, K-Co/Al₂O₃, and Cu-Co/Al₂O₃) are compared in Table (1). The BET specific surface area of K-modified catalyst decreased from 260 m²/g for original Co/Al₂O₃ catalyst to 238 m²/g for K-Co/Al₂O₃ catalyst. Also, the catalyst surface area decreased to 224 m²/g when it was promoted with copper Cu-Co/Al₂O₃. It is important to mention here that many authors [4,11, 13] pointed to the fact that the activities and selectivity of the catalysts in Fischer-Tropsch reaction depend on the available surface area of active sites and structure of the applied catalysts.

On the other hand, it is noted that, the prepared Pt/HY catalyst (of syngas production) possesses the highest value of the surface area and pore volume as compared with Fischer-Tropsch catalysts.

Figure (3) shows the X-ray diffraction pattern of the Co/Al₂O₃, K-Co/Al₂O₃, and Cu-Co/Al₂O₃ catalysts. The XRD peaks show high crystalline property of all prepared catalyst types. The diffraction peaks at 45.7° and 66.6° are attributed to the γ -Al₂O₃ support. No peaks of Cu and K or their compounds are detected, indicating that Cu and K were dispersed on the support as a monolayer or formed spinel-like or tridymite-like structure with no detectable interaction between the promoter and support.

It is important to mention here, that the pretreatment conditions of catalyst preparation play an important role in determining the final specification of catalyst. Therefore, Zsoldos et al. [16] who examined the influence of reduction time (1 to 4 h) on the degree of reduction, found that depending on the reduction time zero-valent cobalt phases of two different structures were obtained. Short reduction times lead to the formation of very small CoO particles, while long-term reduction results in the formation of large, bulk-like crystallites. Then, in the present work the reduction of Co/Al₂O₃ catalyst by hydrogen may be proceeded in two steps: Co₃O₄ to CoO and CoO to Co metal. The first step was completed by the shift of the oxide diffraction of 36.9° (Co₃O₄) to 36.5° (CoO) and appearance of the 42.5° and 61.6° lines. The intensity of these lines depended on temperature of calcinations and reduction as CoO was gradually transformed to metallic cobalt. These observations are in agreement with the work of Agudamu et al. [30].

- Syngas Production (Partial Oxidation of Methane)

The partial oxidation of methane was used in the present work to be the source of syngas CO and H₂ in feed into the Fischer-Tropsch reactor. The advantages of the catalytic partial oxidation of methane over steam reforming of methane are the low exothermicity of the process and the high reaction rates, leading to high selectivity toward CO and H₂ [3,7].

The performance of Pt/HY catalyst is shown in Table (2). The results indicate high methane conversion of about 92.5% over this type of catalysts. On the other hand, the catalyst selectivity toward CO and H₂ were 95% and 96.4% respectively. This may be attributed to the best operating conditions of temperature and gases flow rates. On the other hand, the Pt/HY catalyst possesses a high surface area of 435 m²/g and a large pore volume of (0.63 cm³/g) as shown in Table (1). Then, the platinum metal is highly dispersed on zeolite support according to the applied preparation method which leads to more active sites in the bifunctional catalyst. It is known that the Pt/HY catalyst has the ability to resist the deactivation and works and has long life time.

FISCHER-TROPSCH REACTIONS

Fischer-Tropsch reactions of the Co/Al₂O₃, K-Co/Al₂O₃, and Cu-Co/Al₂O₃ catalysts were investigated at different reaction temperatures ranging from 230 to 270°C. Figures (4), (5), and (6) show the effect of reaction temperature on product distribution in the Fischer-Tropsch reaction. Usually, the bulk of a typical gasoline consists of hydrocarbons with carbon atoms between 4 and 12 per molecule (commonly referred to as C₄-C₁₂). The diesel fuel is the mixture of carbon chains that typically contain between 13 and 21 carbon atoms (C₁₃-C₂₁), while, C₂₃⁺ represents wax of heavy molecular weight hydrocarbons. Therefore, the product distributions in the present investigation are represented in terms of gasoline cut, diesel fuel cut, and waxes.

From the hydrocarbons product distributions that are shown in Figures (4), (5), and (6), it is noted that the Fischer-Tropsch products contain large amounts of normal paraffins. Thus, the Fischer-Tropsch synthesis product is suitable to apply as diesel fuel, rather than for gasoline. The same conclusion was reached by Heng et al. [2], Das et al. [4], and Bartholomew et al. [10]. On the other hand, the catalyst preparation procedure, pretreatment conditions, type of promoter and reaction temperature govern the product distribution and then determine whether light or heavy hydrocarbons are produced. Then, Figures (4), (5), and (6) mainly point to the constant reaction temperature effect on the product distribution. It was concluded that the temperature of 240 °C represents the best reaction temperature for all three types of prepared catalysts (Co/Al₂O₃, K-Co/Al₂O₃, and Cu-Co/Al₂O₃).

Usually, Fischer-Tropsch reactions include a side reaction called the water-gas shift (WGS) reaction which is regarded as the major problem that lowers the desired fuels selectivity [9]. Then, the reaction results indicated that the activity of water-gas shift (WGS) reaction is very small with the incorporation of potassium (K) and copper (Cu) promoters. These promoters can inhibit the hydrogenation ability, suppress the formation of methane, and enhance the selectivities to olefin and higher molecular weight products (i.e. diesel fuel). The same observation was noted by Sadaghiani [8].

The catalytic stability with time on stream is shown in Figure (7). The initial activity is stable for all catalyst types, but, the activity rapidly decreases as the reaction time becomes longer. The performance of Fischer Tropsch catalysts in this case was studied at 240°C (the best reaction temperature). It is important to mention here that the deactivation behavior of cobalt catalysts is mainly due to the following reasons: oxidation of metal cobalt, metal migration into the support lattice resulting in the formation of the inactive Fischer-Tropsch compounds (e.g. aluminate), the aggregation and growth of metal cobalt on the surface of the catalyst and the loss of metal cobalt because of attrition [14, 17]. The results show that the introduction of small amounts of K or Cu has a strong impact on the properties of Co/Al₂O₃ catalyst. Then, the addition of Cu as promoter was found to have a remarkable effect on the deactivation of catalyst during the Fischer-Tropsch reactions as shown in Figure (6). Therefore, the Cu-Co/ Al₂O₃ catalyst is regarded as the most stable catalyst which gives 68% of total CO conversion to hydrocarbon products.

On the other hand, it was observed that as the reactions proceeded the catalyst pore system was filled with waxes products that were formed during the Fischer-Tropsch reactions, thus, affecting the carbon monoxide conversion and then decreasing catalyst activity.

CONCLUSIONS

- 1- The results indicate that the Cu-Co/Al₂O₃ catalyst is the best catalyst in which shows the highest CO conversion of 68 % coupled with good stability.
- 2- The results indicate that the best operating temperature for all catalysts is 240°C. This temperature gives the highest hydrocarbons yield.
- 3- The application of GTL technology in Iraq is important and it is possible to be a new source for clean fuels depending on Iraq natural gas reserves.

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Table (1) Properties of prepared catalysts.

Property	Syngas Catalyst	Fischer-Tropsch Catalysts		
	Pt/HY	Co/Al ₂ O ₃	K-Co/Al ₂ O ₃	Cu-Co/Al ₂ O ₃
Metal & Promoter Content (wt%)	0.5 % Pt	15% Co	15% Co 0.02 % K	15% Co 0.05 % Cu
Surface Area (m ² /g)	430	26.	238	224
Pore Volume (cm ³ /g)	0.63	0.41	0.35	0.31
Chlorine Content (wt%)	0.15	0.22	0.23	0.23

Table (2) the performance of Pt/HY catalyst.

Catalyst	Reaction Temperature °C	CH ₄ Con.%	CO Selectivity %	H ₂ Selectivity %	H ₂ /CO ratio
Pt/HY	700	92.5	95	96.4	2.0



(a)

(b)

Figure (1) View of the full GTL experimental apparatus (two catalytic units in series), (a) Syngas Production Unit (b) Fischer-Tropsch Production Unit.

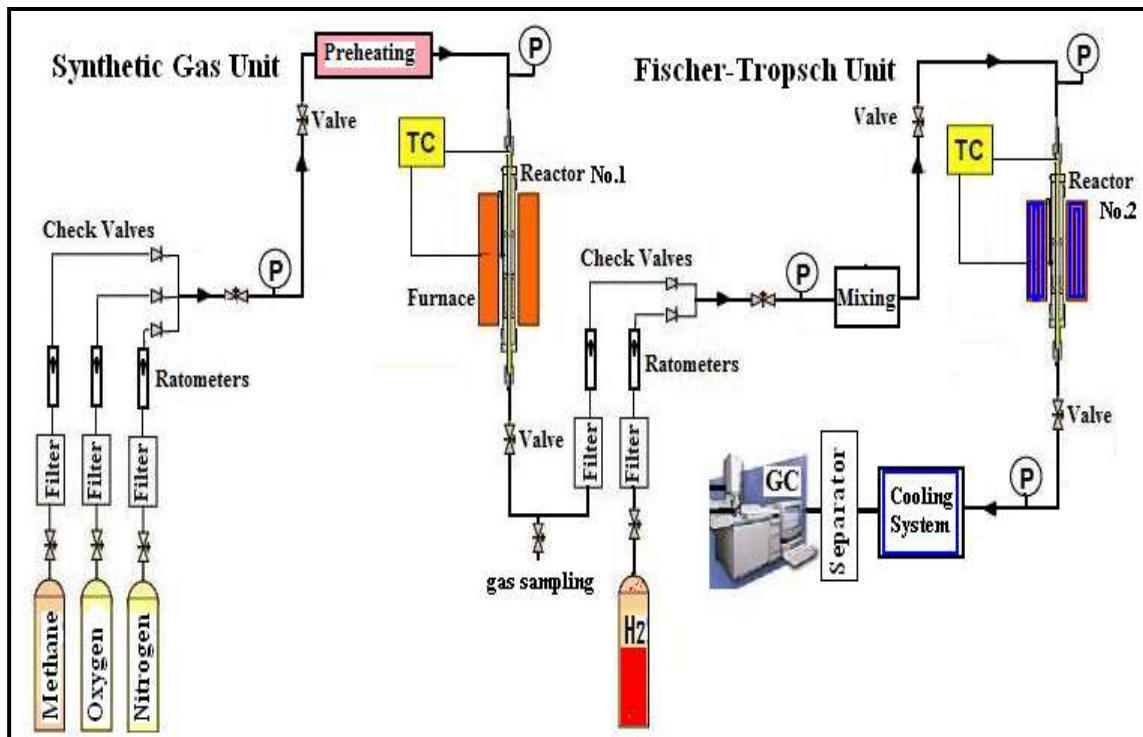


Figure (2) Schematic diagram of the full GTL experimental apparatus.

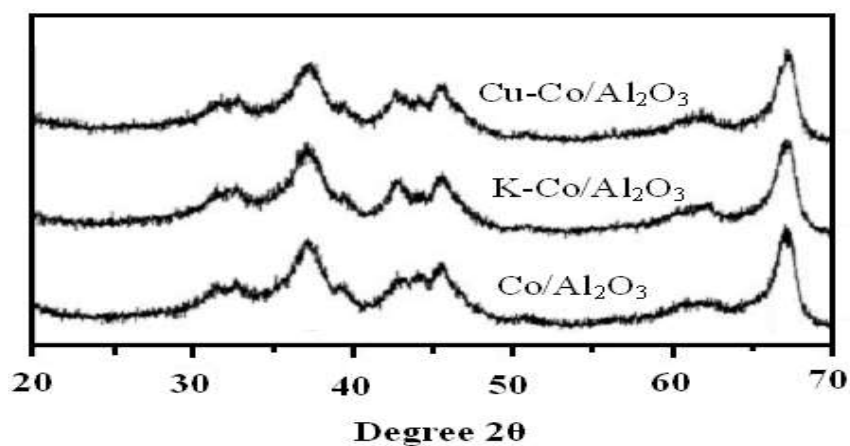


Figure (3) X-ray diffraction pattern of the prepared Fischer-Tropsch catalysts.

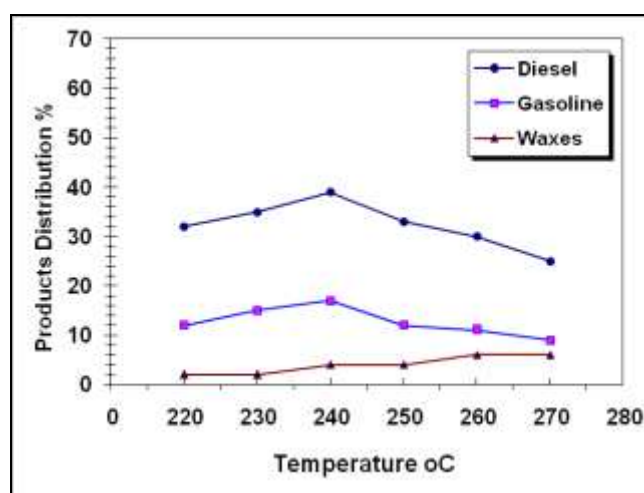


Figure (4) Effect of reaction temperature on products distribution (diesel, gasoline and waxes cuts) using Co/Al₂O₃ catalyst.

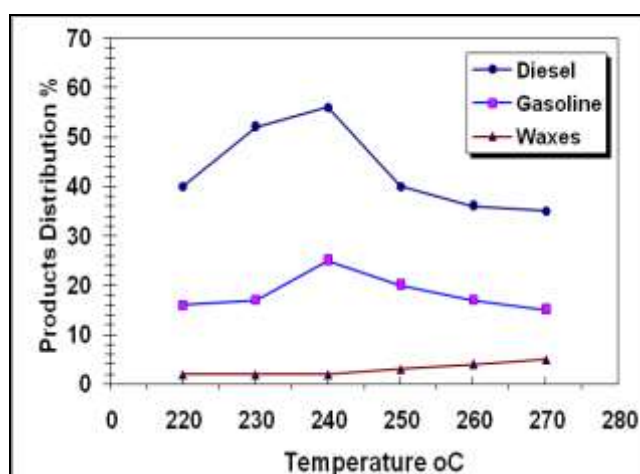


Figure (5) Effect of reaction temperature on products Distribution (diesel, gasoline and waxes cuts) Using modified- Co/Al₂O₃ catalyst.

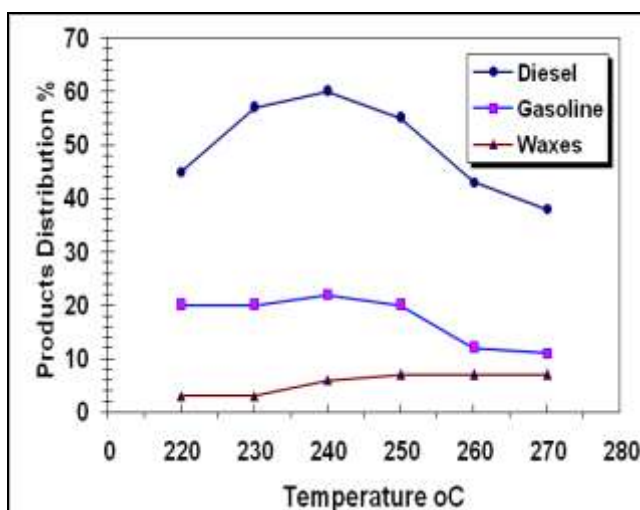


Figure (6) Effect of reaction temperature on products Distribution (diesel, gasoline and waxes cuts) using Modified Cu- Co/Al₂O₃ catalyst.

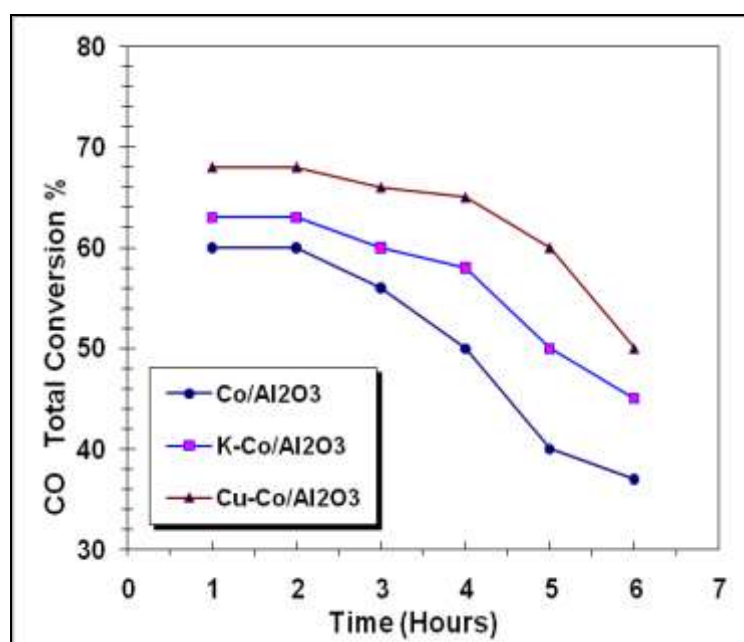


Figure (7) Effect of reaction time on total CO conversion at 240°C (catalysts stability).

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