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# A Technical Roadmap for China's Petrochemical Industry Upgrading to Achieve Carbon Neutrality

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## 1. Introduction

Human's consumption of fossil fuel energy, accompanied by enormous quantities of carbon dioxide ($CO_2$) emissions, is closely related to glacier melting, sea level rise, and the frequent occurrence of extreme weather in the past century. The Intergovernmental Panel on Climate Change (IPCC) put forward the goal of carbon neutrality in October 2018. So far, more than 130 countries and regions around the world have proposed their corresponding goal of carbon neutrality. China has also proposed to achieve a carbon peak by 2030 and carbon neutrality by 2060 [1].

As China's foundational and pillar industry, the petrochemical industry must reduce its $CO_2$ emissions [2]. $CO_2$ emissions from petrochemical processes amount to roughly $4.7 \times 10^8$ $t{\cdot}a^{-1}$ (as of 2019), making up about 5% of China's total $CO_2$ emissions.

## 2. Perspectives on the transformation of China's petrochemical industry

To achieve the necessary reduction of its $CO_2$ emissions, China's petrochemical industry must transform.

### *2.1. The petrochemical source*

Depending on the crude oil composition [3], more than 90% of the $CO_2$ emissions from all petroleum processing in China comes from atmospheric and vacuum distillation for separating light and heavy components, the processing of heavy feedstock, and the hydrogen-production process for the hydrogenation of heavy feedstock. Decreasing the processing of inferior and heavy oil from the petrochemical source and processing a higher proportion of light and low-carbon crude oil can be a major driving force in decreasing $CO_2$ emissions from petrochemical processing.

### *2.2. Petrochemical processing*

#### *2.2.1. Energy conservation and consumption reduction in petrochemical processing*

Reducing energy consumption and improving energy efficiency are crucial in decreasing the $CO_2$ emissions from China's petrochemical industry. In terms of key equipment that produces large amounts of $CO_2$ in petrochemical processing, the industrial furnace is the major energy consumer. Thus, improving the thermal efficiency of industrial furnaces can reduce energy consumption.

In terms of chemical reaction and separation processes, traditional distillation and purification account for about 50% of the energy consumed in the whole petrochemical production process. The application of new adsorption separation, membrane separation, and membrane preparation technologies, along with energy-saving optimization technology for distillation columns, holds great potential for energy conservation and $CO_2$ reduction in petrochemical processes.

#### *2.2.2. Green energy supply and energy-supply electrification*

As the cost of green energy technologies such as wind and solar energy decreases, the electrification of key energy-consuming equipment can effectively replace the current energy-supply mode based on fossil fuel combustion [4]. In addition, the production of hydrogen for petrochemical processes via the green electricity electrolysis of water will replace traditional hydrogen-production processes, such as coal to hydrogen (gray hydrogen) and natural gas to hydrogen (blue hydrogen), thereby decreasing $CO_2$ emissions.

#### *2.2.3. Shortening the process chain and reducing high-intensity processing*

The technology of direct steam or catalytic cracking of crude oil to produce chemicals has the remarkable characteristic of a short process chain; thus, it is expected to greatly reduce the production cost of low-carbon olefins.

### *2.3. End-use of petrochemical product and of $CO_2$ from petrochemical processing*

#### *2.3.1. Increasing the proportion of materials and other high-value-added products*

It is predicted that the consumption of China's petrochemical products will enter a mature period after 2030 and reach a peak around 2040 [2]. Thus, the consumption of China's petrochemical products will continue to grow before China's goal of carbon

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neutrality is achieved. In particular, the demand for high-end synthetic resins, new materials, and other petrochemical products will grow rapidly. Based on research at several institutions [2,5], it is estimated that the proportion of petrochemical products in China's oil consumption structure will rise from the current 35%–40% in 2030 and to more than 50% in 2050.

#### *2.3.2. Concentrating $CO_2$, and carbon capture, utilization, and storage*

The flue gas produced by fuel or coke combustion usually has a low concentration of $CO_2$. In carbon capture, utilization, and storage (CCUS), $CO_2$ capture from flue gas is important for subsequent utilization and storage. Thus, it is essential to increase the concentration of $CO_2$ in flue gas to reduce the capture cost. Furthermore, the utilization and storage of the captured $CO_2$ play a crucial role in achieving negative carbon emissions from petrochemical processing.

## 3. Technical countermeasures

### *3.1. Upgrading typical processing technology*

The fluid catalytic cracking (FCC) process is a key technology for converting low-value heavy oil into high-value light oil products. The $CO_2$ emissions from this process, which are due to the burning of deposited coke on the catalyst, can make up as much as 33% of the total emissions from a refinery. Thus, it is a reasonable choice for refineries to capture the $CO_2$ that is inevitably produced by coke burning and then deal with the captured $CO_2$ through utilization or geological storage. However, traditionally burning coke in air (which is 78% nitrogen, $N_2$) in an FCC regenerator results in a low $CO_2$ concentration (< 15%) in the flue gas. Therefore, the direct capture of this low-concentration $CO_2$ in flue gas requires high energy consumption and has a high capture cost. To reduce the capture cost, it is essential to concentrate $CO_2$ in regeneration flue gas. According to research by the State Key Laboratory of Heavy Oil Processing of the China University of Petroleum (Beijing, China) [6], using a $CO_2 + O_2$ mixture as the oxidant to replace air in the FCC regeneration process results in the main component of the generated flue gas being $CO_2$. Pure $O_2$ can be obtained through air separation using technologies such as pressure swing adsorption (PSA). In this way, the $CO_2$ concentration of regenerator flue gas can be increased to 90%–95%. Part of the flue gas with a high $CO_2$ concentration can be recycled to mix with $O_2$, and this mixture then goes into the regenerator, while the rest of the flue gas can be captured, greatly reducing the cost of $CO_2$ capture. The proposed process is shown in Fig. 1.

Taking an FCC unit with a capacity of $2.6 \times 10^6\ t{\cdot}a^{-1}$ at China Petrochemical Co. (China) as an example, process simulation was performed to compare traditional regeneration with air versus the new regeneration technology with a mixture of $CO_2 + O_2$. It was found that the new regeneration technology can reduce energy consumption by 25 000 tonnes of standard oil per year (Table 1). At the same time, it can reduce $CO_2$ emissions by $600\,000\ t{\cdot}a^{-1}$, which is equivalent to the annual $CO_2$ absorption of 5.3 million 30-year-old fir trees or the annual emission of 300 000 economy cars. Thus, it is clear that the new FCC regeneration process can be used to create a win–win situation in terms of environmental and economic benefits.

A numerical simulation analysis of the coke-burning process in a regenerator revealed that, compared with the traditional regeneration process with air, the $CO_2$ concentration in the flue gas was significantly increased in the regeneration with $CO_2 + O_2$, reaching as high as 95%. A flue gas with such a high $CO_2$ concentration can be utilized directly or geologically stored without the need for absorption and capture, significantly decreasing the cost of CCUS.

### *3.2. Innovative processing technology with low $CO_2$ emissions*

#### *3.2.1. New steam cracking technology for ethylene production via green electricity heating*

Steam cracking to produce ethylene is the main process in the transition from oil refining to chemical production. The steam cracking reaction is essentially endothermic. To provide sufficient heat for heating the feed oil and for the reaction, fuel oil or natural gas must be burned, producing large amounts of $CO_2$. The State Key Laboratory of Heavy Oil Processing of the China University of Petroleum (Beijing) has proposed a new process to upgrade traditional steam cracking by using green electricity to replace fuel oil or natural gas for heating. This new process is expected to greatly reduce $CO_2$ emissions from ethylene production [4].

#### *3.2.2. Mass-transfer intensification technology for heavy oil hydrogenation*

Hydrogenation is one of the main ways of realizing the utilization of residual oil. However, due to the low solubility of hydrogen and its slow dissolution rate in residual oil, it is usually necessary to use high pressure (> 10 MPa) to improve the dissolution rate of hydrogen in residual oil. Achieving this high pressure requires a huge amount of energy, indirectly producing a great deal of $CO_2$. In recent years, based on the research of the hydrogenation reaction process of residual oil, the total reaction rate of residual oil hydrogenation can be improved by using nano- and micro-bubbles with a high specific surface area to intensify the mass-transfer process of hydrogen into residual oil [7]. In this way, the efficient hydrogenation of residual oil can be realized without the need for high-pressure operation, resulting in significant amounts of energy being conserved. At the same time, this technology can decrease the cost of equipment, in a typical example of indirect $CO_2$ emissions reduction through process intensification.

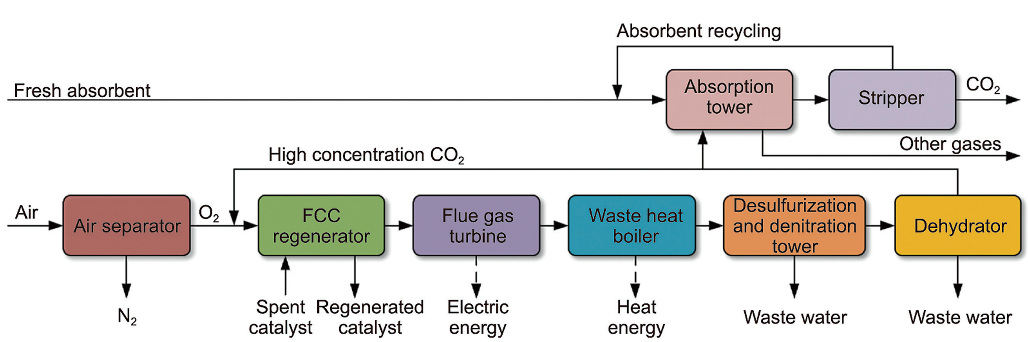


**Fig. 1.** New regeneration process with mixture of $CO_2 + O_2$ for FCC process.

#### 3.2.3. New gasification technology for petrochemical residues

The main processing technology for residue oil is delayed coking, which produces about 30 million tonnes of petroleum coke with a high sulfur content and low economic value in China every year, seriously challenging the efficient utilization of crude oil. The subsequent utilization of such petroleum coke (e.g., for combustion, metal smelting, etc.) results in a large amount of $CO_2$ emissions. The State Key Laboratory of Heavy Oil Processing of the China University of Petroleum (Beijing) has therefore proposed a coupled process of petrochemical residual oil pyrolysis and coke gasification, with green electricity heating [8]. In this process, residual oil is pyrolyzed into light oil under a syngas atmosphere, and coke is subjected to catalytic gasification without oxygen only using the gasification agent of $H_2O$—under green electricity heating to produce high-quality syngas with a $CO_2$ content below 3 v%. This coupled process has nearly zero $CO_2$ emissions. The process involves the efficient pyrolysis of residual oil under a syngas atmosphere, the immediate catalytic gasification of coke after its generation without involving $O_2$ as a gasification agent, the coupling of multiple reaction processes with electric field heating, and the coupling of flow, heat transfer, mass transfer, and the reactions of multiphase materials. The high-quality syngas ($CO + H_2$) produced by the coupled process can be used further in petrochemical processes.

**Table 1**
Comparison between a conventional flue gas treatment process to capture $CO_2$ and the new FCC regeneration process with $CO_2$ enrichment and capture.

| Item | Conventional process + $CO_2$ capture | New regeneration process with $CO_2$ enrichment and capture |
|---|---|---|
| Standard oil for main fan ($kg{\cdot}h^{-1}$) | 5 794.1 | 0 |
| Standard oil for air separation ($kg{\cdot}h^{-1}$) | 0 | 7 600.0 |
| Standard oil for producing steam via heat collector in regenerator ($kg{\cdot}h^{-1}$) | −13 200.0 | −3 784.0 |
| Standard oil for flue gas turbine providing external work ($kg{\cdot}h^{-1}$) | −3 834.2 | −4 099.3 |
| Standard oil for steam produced by waste heat boiler ($kg{\cdot}h^{-1}$) | −6 512.0 | −10 560.0 |
| Standard oil for cooling water separator ($kg{\cdot}h^{-1}$) | 0 | 982.6 |
| Standard oil for $CO_2$ circulating compressor working ($kg{\cdot}h^{-1}$) | 0 | 2 651.7 |
| Standard oil for $CO_2$ capture ($kg{\cdot}h^{-1}$) | 12 474.0 | 2 494.8 |
| Standard oil for input ($kg{\cdot}h^{-1}$) | 18 268.1 | 10 752.4 |
| Standard oil for output ($kg{\cdot}h^{-1}$) | −23 546.2 | −18 443.3 |

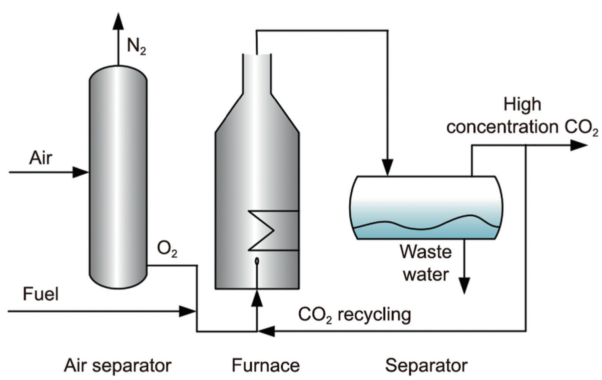


**Fig. 2.** Pure oxygen with nitrogen cut-off combustion technology by flue gas circulation for furnace.

### 3.3. Innovation of key equipment

In the petrochemical industry, furnaces are high-energy-consuming pieces of equipment, accounting for about 40% of the total energy consumption of a refinery. In some units, such as the atmospheric and vacuum distillation unit and the coking unit, the energy consumed by the furnace can reach 90% of the total energy consumption of these units. A high energy consumption results in high $CO_2$ emissions. Therefore, improving the thermal efficiency of furnaces is a reliable path to reduce $CO_2$ emissions.

The combustion method normally used in such furnaces takes air as the oxidant, resulting in a flue-gas $CO_2$ concentration of 10% or lower. The separation and capture of such low-concentration $CO_2$ have a high cost. For this reason, the State Key Laboratory of Heavy Oil Processing of the China University of Petroleum (Beijing) has proposed a combustion technology using pure oxygen with a nitrogen cut-off for the flue gas circulation, to be used in furnaces in the petrochemical industry [9]. The proposed technology is shown in Fig. 2.

This technology uses pure oxygen as the oxidant and circulating flue gas, with $CO_2$ as the main diluent. After being mixed with the fossil fuel, $O_2$ and $CO_2$ are then introduced into the furnace for combustion. Once the water vapor has been removed from the flue gas, the $CO_2$ concentration can theoretically reach higher than 95%. Such a high concentration of $CO_2$ can be utilized or geologically stored even without capturing, greatly reducing the cost of realizing zero $CO_2$ emissions from the furnace.

In the long term, changing the energy supply of furnaces and fundamentally realizing zero $CO_2$ emissions from furnaces are an important direction in the petrochemical industry. In regard to the source of heating energy, it will be a realistic choice for furnaces to use green electricity generated from wind and solar energy. Taking a steam cracking furnace for ethylene production as an example, green electricity generated by wind and solar energy can be used to replace fossil fuel combustion in providing heat for the cracking reactions of the feed oil to produce ethylene, in what will be an important part of industrial "re-electrification."

## 4. Outlook

Petrochemical processes are typical industrial processes with high energy consumption and high $CO_2$ emissions. The petrochemical industry plays a very important basic role in China's economic and social development. However, the petrochemical industry also faces urgent pressure to transform and upgrade in order to enable China to achieve a carbon peak and carbon neutrality. For the future upgrading of the petrochemical industry, the following perspectives are proposed:

First, regarding the petrochemical source, lightweight, low-carbon, and diversified raw materials should be used for processing. Second, regarding processing, it is necessary to achieve energy conservation and consumption reduction, along with a supply of green and electric energy. Other necessary improvements include shortening the process flow, reducing the processing intensity, increasing the proportion of material products, and improving the CCUS of the $CO_2$ generated from the petrochemical processing.

A technical path to realize $CO_2$ emissions reduction is expected to be achieved through combined efforts in typical process upgrading, low-carbon process innovation, and the $CO_2$ emission reduction of key equipment (e.g., FCC regenerators and delayed cokers). Through the upgrading and transformation of these processes and equipment, it is expected that a more than 90% reduction in $CO_2$ emissions from the entire petrochemical industry can be achieved, making this a practical path choice for enabling the petrochemical industry to achieve the goal of a carbon peak and carbon neutrality.

It should be mentioned that, although the present work discusses petrochemical industry upgrading in China, the perspectives and the technical path proposed herein to realize $CO_2$ emissions reduction in China are also applicable across the world.

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