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REVIEW

FCC riser quick separation system: a review

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Abstract The riser reactor is the key unit in the fluid catalytic cracking (FCC) process. As the FCC feedstocks become heavier, the product mixture of oil, gas and catalysts must be separated immediately at the outlet of the riser to avoid excessive coking. The quick separation system is the core equipment in the FCC unit. China University of Petroleum (Beijing) has developed many kinds of separation system including the fender-stripping cyclone and circulating-stripping cyclone systems, which can increase the separation efficiency and reduce the pressure drop remarkably. For the inner riser system, a vortex quick separation system has been developed. It contains a vortex quick separator and an isolated shell. In order to reduce the separation time, a new type of separator called the short residence time separator system was developed. It can further reduce the separation time to less than 1 s. In this paper, the corresponding design principles, structure and industrial application of these different kinds of separation systems are reviewed. A system that can simultaneously realize quick oil gas separation, quick oil gas extraction and quick pre-stripping of catalysts at the end of the riser is the trend in the future.

Keywords Fluidization · Quick separation · FCC · Post-riser system

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1 Introduction

Fluid catalytic cracking (FCC), one of the most important conversion processes used in petroleum refineries, transforms the low-value heavy crude oil into a variety of high-value-added light oil products. Up to now, the total capacity of FCC units (FCCUs) in China has reached 150 Mt/a, of which the outputs roughly account for 70 %, 40 % and 30 % of gasoline, propylene and diesel pools, respectively. However, in recent years, the reaction temperature and cracking degree have increased to a large extent with the feedstocks becoming heavier and inferior. As a result, the incidental high coke formation rate may threaten the operation safety in some refineries. Two factors contribute to the coke formation: (1) long residence time of the mixture of oil, gas and catalysts in the separator and (2) the severe back-mixing of oil gas in the disengager (Li et al. 2011; Karthika et al. 2012; Xu 2014; Gao et al. 2013; Dong et al. 2013; Wang et al. 2016). To solve these problems, a series of efficient separation systems at the riser outlet have been developed. These separation systems concentrate on separating the production and catalysts as soon as possible. Besides, they should reduce the residence time of oil gas in the reaction systems (gas–solid separation unit and disengager) simultaneously. Technologies which can simultaneously realize quick mixture separation and reduce oil gas residence time in the reaction system have been studied. Results show that the separation systems have brought huge economic benefit for chemical industries all around the world.

2 Early technologies

The early industrial separation systems are shown in Fig. 1. The earliest versions are T type, inverted L type and clover type. In order to increase the separation

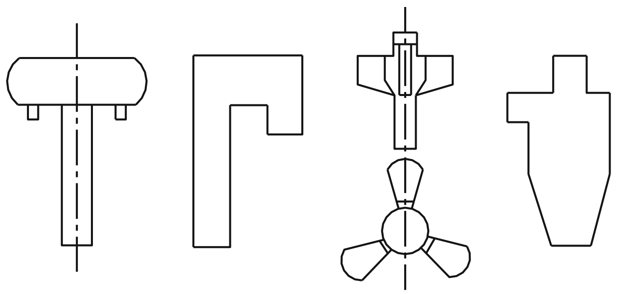

Fig. 1 Schematic diagram of the quick separation systems used in the outlet of the early riser reactor

efficiency, the improved version called the rough vortex quick separation system was developed in 1990 (Amos and Avidant 1990). These systems with simple structures all use inertia force to separate the mixture. The separation efficiency has been improved to some degree with the optimization of the structures. However, problems like back-mixing and coke formation were not taken into consideration.

Table 1 shows the comparison of these four types of quick separation systems. It can be seen that T-type, inverted L-type and clover-type separation systems use inertia force generated by 180° rotation of gas and solid to separate the oil gas and catalysts, while the rough vortex quick separation system uses the centrifugal force resulted from the high spinning velocity. The T-type and inverted L-type separation systems usually use two-stage top cyclone separators in series to raise the separation efficiency. However, the pressure drop of the system is high and the residence time of oil gas is very long (about 20 s), which can result in severe coke formation problems. The improved rough vortex separation system uses only a one-stage top cyclone to separate the mixture. It shortens the residence time of gas oil and raises the separation efficiency to almost 98 %, but the high pressure drop is a threat to stable operation of the process. Though the rough vortex quick separation system has had many improvements recently, the separation efficiency of it still does not meet the requirements of the industry. Besides, the long contact time of mixture in the disengager can result in coking problems.

3 Foreign technologies

Foreign researchers have been working on the optimization and development of quick separation systems for a long time. Some technologies have already been applied to the industry production, and remarkable results have been achieved. These quick separation systems include the vortex disengager stripper (VDS) system and vortex separation system (VSS) from UOP Company (Gilbert 1995), the Rams horn system from the Stone & Webster Company and the closed cyclone technology from Mobil Company.

3.1 VDS system and VSS

For the first time, UOP Company (USA) developed a separation system with a closed cover outside the riser, namely VDS system and/or VSS. The VDS system has a stripping unit at the bottom of a rough vortex separation system and forms a two-stage stripping system. The rough cyclone standpipe is connected to the top cyclone entrance which forms a ring, and this ring makes the stripper gas flow into the VDS system easily. For the vortex separation system, a tube with a bent wall (split head) is located at the riser outlet to separate the mixture. Outside the split head is a sealed cover. The connection between the standpipe and top cyclone entrance is different from the VDS system (Gauthier et al. 2000; Chen and Brostem 2001). Figure 2 shows the basic structures of these two separation systems.

The common characteristic of VDS and VSS systems is that the oil gas and stripping steam flow through the quick separation system. Thus, the residence time is reduced dramatically with separation efficiency unchanged, and the coking problem is eased. It is reported that 98 % oil and gas flow out of the separation system with the residence time being decreased to around 6 s by using the VDS and VSS systems (UOP). In addition, compared with the traditional T-type separation system, VDS and VSS systems provide high gasoline yield, with decreased dry gas yield and coke formation (Tian and Zhang 2013).

3.2 Rams horn system

Stone & Webster Company (USA) developed a riser terminal device named the Rams horn separator (axial separator).

Table 1 Comparison among early technologies of quick separation systems

	T type; inverted L type; clover type	Rough vortex separation system
Principle	Inertia force	Centrifugal force
Pressure drop	Less than 1 kPa	About 2–4 kPa
Residence time	About 20 s	8–10 s, about 10 % oil gas back-mixing
System construct	Two-stage series of top cyclone	Single-stage of top cyclone
Problem	Severe coke formation	Severe coke formation

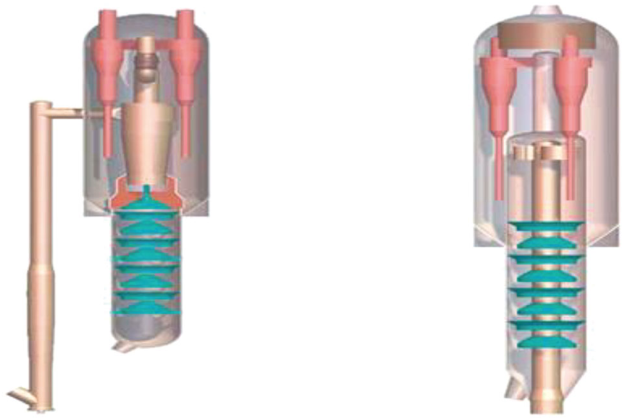

Fig. 2 Basic structures of the VDS and VSS systems

It can reduce the oil gas residence time in the disengager (from 15–51 to 4–9 s by recorded data), decrease the pressure drop and accelerate the gas solid separation (Gauthier et al. 2005). This system uses centrifugal force generated by 180° rotation of the oil/gas mixture and catalysts. So it can prevent catalyst particles from entering the fractionating tower and enables easy operation. As a result, the reaction temperature in the disengager can be lowered by 10 % with light oil yield increasing by about 2 %; meanwhile, the dry gas yield and coke formation can be decreased.

3.3 Closed cyclone technology

Mobil Company and Kellogg Company have developed a high-efficiency closed cyclone technology which can reduce secondary reactions and increase the desired products as well as the total liquid yield (Quinn and Silverman 1995). The main characteristic of this technology is that the catalysts and oil gas directly flow into the first cyclone separator located at the end of the riser. After the first stage of separation, the oil and gas mixture enters the second cyclone separator for further separation with a small amount of catalysts, which can effectively shorten the average contact time of oil with catalysts. The dry gas yield decreases, and the total liquid yield increases (Zhao et al. 2006). Using the tracer (helium) determination method, it is found that the closed cyclone technology can shorten the average residence time of oil and gas reaction process in the open riser from 20 s down to about 2 s with little back-mixing problem.

4 China's technologies

In China, the clover-type and rough vortex separation systems are widely used in FCC process. There are a few units still using the old T-type and inverted L-type separation systems. As mentioned above, these technologies are relatively behind the foreign technologies. In 1994, China University of Petroleum, Beijing, started to concentrate on developing new and efficient quick separation technologies. By now, many types of highly efficient separation systems have been applied in industry successfully, including the fender-stripping cyclone separation system (FSC), the vortex quick separation system (VQS) and the circulating-stripping cyclone separation system (CSC; Hu et al. 2008).

These three separation systems can quickly separate gas and solid, quickly pre-strip catalysts and quickly withdraw oil gas from reactor simultaneously. Besides, there are many other advantages such as no restrictions on unit start-up, good operating flexibility, high separation efficiency and good product distribution.

4.1 FSC system

Currently, the separation efficiency of rough cyclone separators is more than 98 %. Research has reduced the oil gas residence time by extending a rough vortex standpipe adjacent to the top cyclone entrance. The rough vortex dipleg operates with a positive pressure, which means part of the oil gas is also discharged through the dipleg with the pressure impact (the pressure in the dipleg is greater than that in the disengager) besides the dense-phase catalysts. The oil gas moves upward with a velocity of 0.1 m/s, through the 10 m of trip, and then enters the top cyclone.

Figure 3 shows the structural schematic diagram of the FSC system. This system mainly consists of four parts: riser, rough cyclone, pre-stripper and stripper burden surface. In the FSC system, the traditional rough cyclone dipleg is changed into a pre-stripper with a unique structured baffle inside. This baffle has a skirt border which can form a thin layer of catalysts on the baffle plate; thus, the pre-stripping efficiency can be improved. A socket connection structure located between the rough vortex standpipe and top cyclone outlet can achieve quick extraction of gas and oil (Lu and Shi 2007).

The characteristics of this system are shown as follows: The lower part of the pre-stripper is set downstream to absorb the oil and gas deposited on the catalysts easily. The pressure drop changes from positive to negative to extract the oil gas quickly. By this way, the separation efficiency can be improved to some extent. The connection between the rough cyclone and the top cyclone is open and flexible, which means the entrance is large, and it makes gas come out easily.

4.2 CSC system

Different from the baffles in the FSC and VQS systems, in the CSC system, a draft tube is set in the middle to increase

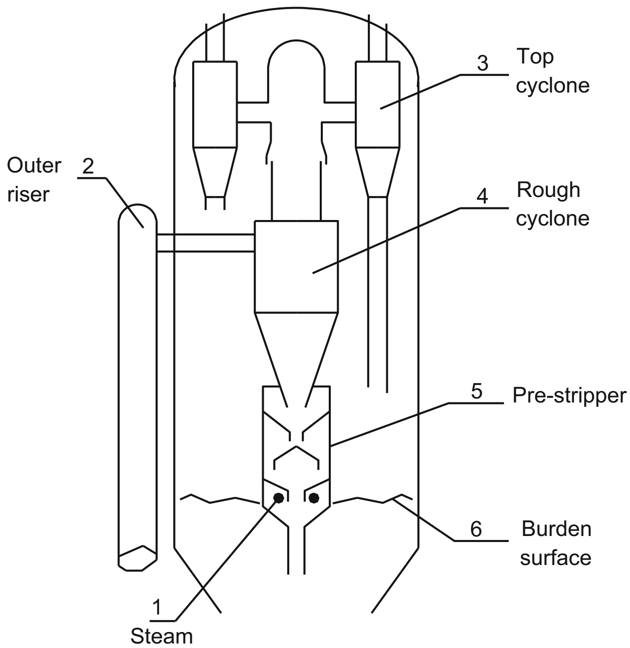

Fig. 3 Basic structure of the FSC separation system

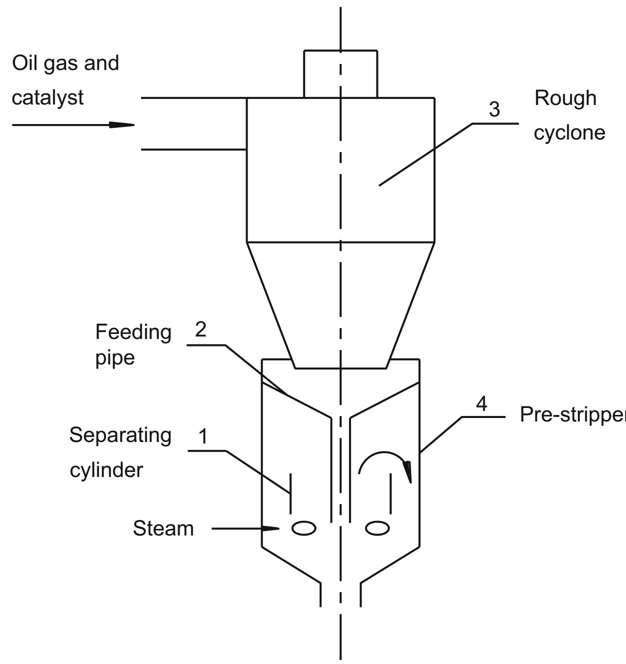

Fig. 4 Basic structure of the CSC separation system

the contact time of catalysts with steam. This kind of system has many advantages such as good stripping results, low coke formation, reduced dry gas yield and improved light oil yield (Rao et al. 2011).

Figure 4 shows the structure of the CSC system, which consists of three parts: rough cyclone with optimized structure size; dense-phase circulation pre-stripper with central feeding pipe; and socket-type (or open straight connected) fast oil gas withdrawal device. The oil gas residence time in the disengager is decreased; hence, this reduces secondary cracking and improves the product selectivity (Xia 2014; Pan 2011). Currently, 13 sets of the CSC system are being used industrially in China, and they can effectively reduce the coke formation and improve the light oil yield.

4.3 VQS

Due to its compact structure and excellent capability, the VQS also has the advantages of the FSC system. As shown in Fig. 5, a separator head is located at the riser outlet, and some baffles are settled under the sealed cover. In this system, the moving direction of oil gas and catalysts is changed into horizontal by the uniquely designed separator head located at the riser outlet. Therefore, the strong centrifugal force is generated by the rotation of catalyst particles, which results in a high separation efficiency and good product distribution.

This VQS is mainly used in heavy oil catalytic cracking units with large-scale inner risers. Researchers in China have tested the operation conditions of the VQS in a cold

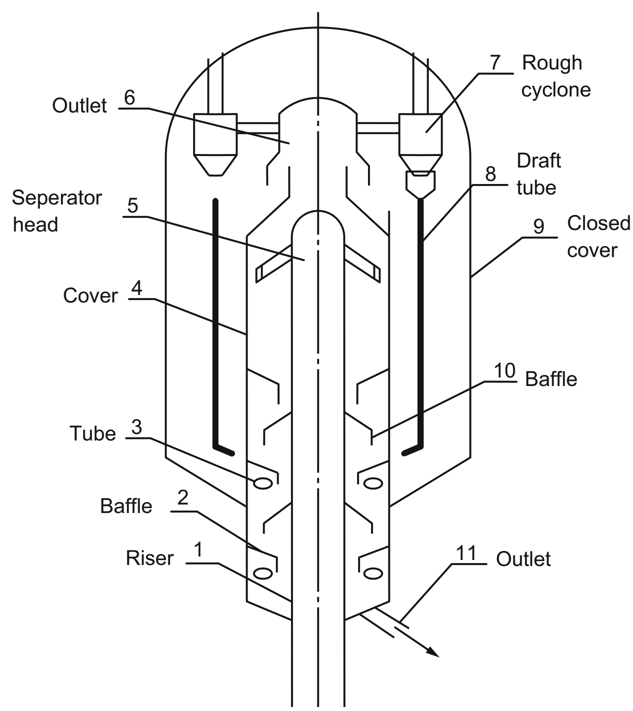

Fig. 5 Basic structure of the VQS

mode FCCU, and the results show that it has start-up flexibility, high gas–solid separation efficiency and improved product distribution (Sun et al. 2004; Lu et al. 2004; Hao and Cheng 2013; Mi 2014).

The VQS can simultaneously realize quick oil and gas separation, quick oil and gas extraction and quick pre-stripping of catalysts at the end of the riser. The pressure

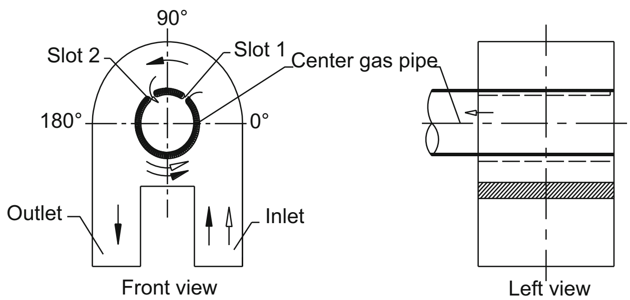

Fig. 6 Basic structure of the SRTS separation system

distribution is reasonable and pressure drop is low, which can prevent gas from gathering and jamming at the outlet. The solid catalyst particles are quickly and efficiently separated; hence, the gas residence time is shortened and the separation efficiency is enhanced. The total gas–solid separation efficiency at ambient temperature exceeds 98.5 %. The application of the VQS in the Sinopec Branch Jiujiang Company Refinery has achieved satisfying results. Their feedstocks have high viscosity and high carbon content. In September 1999, Sinopec Branch Jiujiang Company Refinery replaced the single rotation rough cyclone with a VQS to improve heavy oil processing capacity, reduce coking formation, prolong operating period and increase light liquid yield, and received great economic returns. From the data collected in the refinery, it is found that the products distribution is improved: The dry gas yield is reduced by 0.5 percentage points, and liquid yield increases by 1.2 percentage points.

4.4 SRTS system

The residence time of the oil gas and catalysts in the separation systems introduced above is still over 5 s, which means that coke formation is still a problem. In order to shorten the contact time between oil gas and catalyst particles in the separator, China University of Petroleum (Beijing) has developed a new type of quick separation system with an arch-shaped shell named SRTS (short residence time separator, SRTS), and its structure is shown in Fig. 6. It has a central gas pipe, which is a guiding pipe with two slots along the circumferential direction. One end is in the separation chamber, while the other one extends out of the chamber and is connected with the subsequent separation system (Lu et al. 2008a, b). The gas oil and catalysts flow in the chamber through the inlet and enter in the center gas pipe. Under the effect of centrifugal force, the catalysts are thrown to the shell wall, while the oil gas is extracted through the slots of the gas pipe. The structure of SRTS system is similar to the 'goat head' separation system developed by Mobil Company (USA). The extraction time of oil gas shortens obviously after rotating a half circle in the separator. Although SRTS system has a lot of advantages compared with many other stable quick separation systems, but at present, the knowledge about this new type of separation system is limited. Meanwhile, there still is a lot of research work to be done before it is applied in industry.

5 Future

Our own separation technologies have wide applications. They can solve the unscheduled shut-down problem caused by coke formation in the disengager. Compared with the foreign separation systems, our separation systems have higher separation efficiency, larger operating flexibility and less cost, as shown in Table 2.

The focus of the above technologies is to reduce the residence time of oil gas and catalysts at the end of the reactor. However, for the quick separation unit, limited by its work mechanism, the gas–solid separation time is not reduced dramatically (the oil gas residence time is around 1–2 s). In that case, separation technology, which can realize ultrashort residence time, is required to further decrease the residence time of oil gas in the post-riser system.

Based on the knowledge of the gas–solid separation and experience in industrial application, China University of

Table 2 Comparison between China's new separation technologies and the foreign ones

Technology	China's system	Foreign VDS and VSS systems
Pre-stripping method	Pre-stripper	Empty cylinder
Unloading catalysts	Little negative	Positive
Extracting	Socket	Straight
Efficiency	99 %	95 %
Residence time	<5 s	<5 s
Flexibility	Large	Small
Reforming cost (per unit)	<2 million RMB	>20 million RMB
Application	57 U	5 U

Petroleum (Beijing) has been working on the development of this separation technology for more than 20 years (Liu et al. 2005, 2007; Lu et al. 2007, 2008a, b; Yan et al. 2007). This technology takes the advantages of both inertial and centrifugal separators. The inertial separator has short residence time but low separation efficiency, while the centrifugal separator has long residence time but high separation efficiency. The inertial separation is coupled with centrifugal separation, the separation efficiency is guaranteed by centrifugal separation, and the residence time is shortened by inertial separation. This technology features high separation efficiency, low pressure drop, compact structure and operation stability. Previous research results have shown that the residence time of oil gas in the separator is less than 0.5 s. At the same time, the separation efficiency is up to 99 %, while the pressure drop is only around 3 kPa, which is far less than the conventional rough vortex (6–8 kPa; Wang et al. 2016; Xia 2014).

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