POWER RECOVERY SYSTEMS AND HOT GAS EXPANDERS

by

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John P. Bafoorst was born of Dutch parents in the East Indies. He was educated in Holland and graduated from the Maritime Academy in Amsterdam in 1940. During World War II, he served as an Engineering officer on board troop ships in the Atlantic and Pacific theaters. After the war, he was employed by the Shell Oil Company and was assigned as an Equipment Engineer at the Shell-Houston Refinery. In 1949, he became an American citizen.

He has been intimately involved in the design, application, selection, construction, inspection, initial start-up and maintenance of all mechanical equipment, especially in the early stages of high speed, high pressure centrifugal barrel type compressors in hydrogen recycle service in catalytic reformers. He has also been involved in large gas turbine installations and power recovery systems in fluid catalytic cracking units.

Mr. Bafoorst was promoted to Senior Engineer and then to Staff Engineer in 1966. He has been on loan to all other Shell Refineries in the United States to check out and start up mechanical equipment in new process units. In 1967, he was assigned to the Expansion-Construction Department and became Group Leader for the Mechanical Equipment Group. After construction was completed, he was reassigned in 1971 to the Engineering Services Department where he is presently in charge of the Mechanical Equipment Section.

In 1972, Mr. Bafoorst was promoted to Senior Staff Engineer.

INTRODUCTION

As the cost of energy has always been a substantial factor in the overall cost of oil refining, engineers have devoted a great deal of attention to recovering the available energy in the high temperature flue gas of Catalytic Cracking Units.

The generally accepted method to recover the heat has been to channel the flue gas through a CO burning boiler or process furnace.

In this method, however, a large amount of the available energy is wasted because of required throttling of the flue gas (40-70 BTU/#)

A more efficient design, therefore, required the replacement of the throttling devices but also necessitated the development of two major system components.

1. A turbine to allow the gas to expand thereby converting energy into mechanical power. The turbine design premise was set to allow continuous operation at 1200°F and sustain rapid temperature increases to higher temperature levels for short periods of time during unit upsets.

2. A separator to protect the turbine from highly erosive catalyst particles present in the flue gas stream. The separator design necessarily called for very high efficiencies in removing the catalyst particles, and at the same time retain high resistance to erosion for long periods of time.

Since 1963, the Shell Oil Company of the United States and Shell Canada Ltd. have installed 4 power recovery systems in their manufacturing facilities employing separators and hot gas expanders to generate the required power for the Catalytic Cracker main air blowers. In 1970, Shell Berre installed a power recovery system in the Pauillac Refinery in France. In addition, three CCU power recovery systems have been licensed to other oil companies.

DISCUSSION

Figure 1 illustrates schematically the power recovery train integrated into a new Catalytic Cracker Unit in Shell’s Martinez Refinery in 1966.

The regenerator flue gas, after passing through two internal stages of conventional type cyclone separators is channeled through duct work into the third stage separator where all, but a fractional minimum, of the catalyst particles left in the flue gas are separated. The clean gas is then expanded through a turbine where energy is converted into mechanical power. The gas leaving the expander at a temperature of 950°F and containing about 8% CO is then channeled into CO burning boilers where the remaining heat is utilized to generate steam for plant use. As the expander acts as a fixed orifice, the regenerator pressure is maintained by a full size 60” butterfly type control valve located between the separator and expander. The expander with an inlet pressure of about 20 PSIG and inlet temperature of 1200°F develops 15,500 horsepower.

Other equipment in the train includes a 130,000 SCFM axial air blower, a 10,000 HP steam turbine, and a 4,000 HP motor-generator. The steam turbine is used to start the entire train; the motor is activated later in the startup procedure when a higher speed is required. During the initial stages of startup the expander absorbs energy but as the flue gas pressure and temperature are increased, the expander begins to develop power. The steam turbine output is automatically reduced and eventually will cease to supply power altogether. The steam turbine will then continue to windmill. The electric motor converts to a generator when the operating speed of 3,600
RPM is reached, and will, under normal operating conditions, absorb the excess expander power (2,500 HP). Figure 2 shows a photographic view of the power recovery train. The Houston power recovery train, which is of an earlier design, is shown in Figure 13.

THIRD STAGE SEPARATOR

The regenerator flue gas, entrained with catalyst, enters the separator vessel through a 62° centrally located inlet pipe and is distributed through a screen between two tubesheets and into separator tubes. In these tubes the heaviest catalyst particles are separated from the flue gas and leave the vessel with a minimum amount of flue gas (2-4%) through a 20° outlet and a critical flow nozzle to a catalyst disposal system. The clean gas leaves the separator through a 60° outlet and flows through the regenerator pressure controller into the expander turbine.

Figure 3 shows a cross section of the separator. The vessel, 26' diameter, is of the cold shell design and is internally lined with 4" insulation and erosion resistant material. The 2-4\% chrome concave tubesheets are suspended from the carbon steel shell and are connected to the inlet pipe through an expansion joint to allow for differential expansion during unit upsets. The concave tubesheets hold the separator tubes. Pressure drop across the separator tube is about 1.5 PSI and across the entire separator less than 3 FSI.

CATALYST SEPARATOR TUBE

Figure 4 depicts the separator tube. The catalyst-laden flue gas enters the outer tube and is given a swirling motion as it flows down the tube. The catalyst particles are centrifuged against the tube wall and are separated when the gas flow reaches the bottom and reverses direction. The catalyst particles exit the tube in a continuous flow through the annulus and two blow-down slots, while the clean gas continues to flow upwards and through the inner tube into the separator top section and out to the expander turbine.
Figure 3 — Martinez Third Stage Separator Vessel—Cold Shell Design

The liner in the outer tube is made of Harbisen Walker Korundal ceramic refractory material. Any foreign material too large to pass through the annulus will continue a circular grinding motion until it is small enough to pass through, thereby preventing the slots from plugging.

During normal operating conditions, the separator takes in 550,000±/hr of flue gas which contains about 300±/hr of catalyst particles ranging from ½ to 60 microns in size. About 86% by weight is larger than 10 microns. The separator is designed to remove most of the catalyst particles larger than 10 microns. The catalyst fines (10 micron and smaller) will have little detrimental effect on the expander blades.

EXPANDER TURBINE

The design of the Martinez expander turbine is shown in Figure 5. The inlet casing is equipped with an axial inlet and guide vane assembly designed to equally distribute the fine catalyst particles to insure uniform erosion throughout the expander. Expander materials of construction were selected to withstand this high temperature erosion.

To facilitate easy removal, blades are inserted axially into the rotor disc. The trailing edges of these blades are thicker than those in conventional turbines in order to provide additional metal to extend the life of the blades.

To keep catalyst fines from entering the bearing housing, a labyrinth seal, in conjunction with a steam and air injection-ejector system, is installed between the rotor disc and the bearing housing.

To eliminate the necessity of disturbing the massive exhaust duct for rotor inspection or removal, the expander was designed to allow the bearing pedestal and rotor assembly to be backed out of the exhaust casing. This design necessitated a 60° long spacer coupling.

Figure 6 is a photographic rear view of rotor and bearing assembly. The nozzle ring is in the background.

Figure 7 shows a completely assembled expander.

EQUIPMENT DEVELOPMENT

During the 1950’s a tremendous amount of research and development work was performed to improve separator tube efficiency and resistance to erosion.
Since the original commercial installations in 1963, improvements have been made in the design of the separator tube, which, of course, is the most important component of the entire system. The separator vessel has also undergone design and material changes.
In 1964 on-stream rotor blade photography was developed to monitor blade erosion. Various blade materials were incorporated into a single rotor and material testing was conducted in the Houston expander between 1964-1967. Tungsten carbide flame coated A-286 blade material was found to have superior erosion resistance for the Houston expander operating with an inlet temperature of 1150°F. For higher temperatures of 1200°F, the Martinez flame coated Inconel X blade material is a better choice.

Blade photography also enable the engineer to correlate expander power loss with blade erosion.

Figures 8, 9, 10 and 11 show photographs taken on-stream of four sets of flame coated A-286 blades in various stages of erosion from the same rotor after 4-200-600-750 days of operation. During this period of time, three unit upsets were recorded.

OPERATING RELIABILITY

Originally, Martinez's design incorporated a 100% flue gas bypass to maintain unit operation in case of separator or expander problems. The steam turbine and motor-generator were sized to supply full horsepower to the main airblower with the expander disconnected. This emergency situation has never developed and the bypass has been taken out of service.

With the continued improvement of the third stage separator, rotor blade performance has increased to a point where 3 to 4 years of blade life can be expected without significant power reduction due to erosion.

Twenty-eight years of experience have been accumulated by Shell with three power recovery units in the United States. Two units have operated in excess of 10 years. Experience has indicated that recovery power systems require no more attention than other unit equipment components, and are not the limiting mechanical component for extended catalytic cracker runs.
OPERATION AND MAINTENANCE

The normal day by day operation in the last 10 years of Catalytic Cracker Units equipped with power recovery systems have proven that these units have the same reliability as any other Catalytic Cracker employing conventionally driven main air blowers.

Operators have learned to cope with unit upsets and flue gas afterburns, and have learned to operate the power recovery unit efficiently.

The expander turbines have operated satisfactorily and have withstood numerous flue gas afterburns. However, on one occasion the expander incurred mechanical damage when the Martinez inner exhaust casing warped to such an extent that it caused an internal rub and caused an unscheduled shutdown. At no time has there been contamination of the lubricating oil by catalyst fines.

Separator maintenance has been performed during normal unit turn-arounds and consisted of cleaning the interior of catalyst, visual inspection of joints, welds, insulation refractory and the ceramic liners.

Expander maintenance has included replacement of rotor blades, nozzle ring and shroud. Bearings and seals have given excellent service and have required only minor maintenance. The cantilever type rotor has run vibration free under all operating conditions even with badly eroded blades. We have experienced no alignment problems to date. A spare rotor, less blades, is shared by three refineries. However, each refinery stocks its own spare parts such as rotor blades, stator blades, shroud, bearings and seals.

SUGGESTED SYSTEM COMPONENT DESIGN

Up to 30% of increased flue gas energy has been observed during unit upsets with high pressure and temperature excursions. To absorb the surplus energy the following design criteria may be applied:

1. Install a "clean" partial bypass to limit the expander output horsepower.

2. Design the motor-generator and pressure control system large enough to absorb all of the excess energy.

3. Install an air blower blast-off to help control regenerator temperatures.

4. Install a 100% air blast-off to be opened only during an emergency situation when all air must be diverted from the regenerator.

Because the steam turbine is only used for startup and windmills during normal unit runs, only a minimum cost single valve turbine need be specified with an atmospheric exhaust. This way no cooling steam is required.

Design turbine horsepower depends on individual unit requirements for “boot strap” startup operation. Remember, the expander will absorb energy at the beginning of the startup.

Figure 12 illustrates a recommended power recovery installation.

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**Figure 12 — Recommended System for Future Power Recovery Installations in Fluid Catalytic Cracking Units**
CONCLUSION

The Shell Oil Company has succeeded in utilizing the available energy previously wasted by throttling the flue gases of Catalytic Cracking Units. The four power recovery systems that were installed in the 1960's have provided Shell with about $15,000,000 in energy savings.

With the continuing increases in energy costs, we would expect that power recovery systems have become a necessity for efficient plant operation.

ACKNOWLEDGMENT

Expander photographs courtesy of Ingersoll-Rand Company.