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PYROLYSIS FURNACE TUBE DAMAGING AND INSPECTION

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Abstract: *This paper explain the most occurring failure mechanisms for pyrolysis furnace radiant tubes. Basic damaging mechanism is the combined action of carburization and creep ductility exhaustion. This results in bulging, bending and ovalization of the tubes. The second dominant failure mechanism is brittle fracture during furnace trips, which can result in large, longitudinal cracks on many tubes.There are several methods for estimating and damage detection of furnace tubes. In assessing the state of furnace tubes we use an optimal combination of methods, as individual methods cannot detect any potential damage. The methods are related to the assessment of damage due to creep, and the material carburization which underlying the creep.*

Keywords: *pyrolysis furnace, furnace tube, tube inspection*

INTRODUCTION

Pyrolysis coils in ethylene cracking furnaces (Fig. 1) are exposed to very severe conditions, e. g. high temperatures up to 1150 °C, severe start/stop and decoke cycles, oxidizing and nitriding flue gases at the outside and carburizing atmospheres at the tube inside surface. Therefore, high-alloyed centrifugal cast Ni-Cr-Fe alloys with adequate high temperature corrosion resistance, good high temperature strength, good machinability and weldability (even after years of service) are required.

Radiant coils have a limited life and failure is caused by a variety of factors, many being related to furnace operation. However, each pyrolysis plant experiences specific operational conditions and operational philosophies. Therefore, each plant has typical causes for radiant coil failure and it is of importance for operators to analyze and to understand the typical failure mechanisms. This will enable them to consider the material grades, which would be best suited for those particular conditions and also to keep failures within limits by proper furnace operation. Mechanisms which causing the majority of failures in radiant tubes are: coke formation, creep ductility exhaustion, thermal fatigue, brittle fracture, erosion, overheating, human factor, creeping, carburization, oxidation, nitridation, chromium evaporation. Tube sheets and tube supports should be examined to determine their physical condition and fitness for further service. Supports should be examined carefully for cracks, oxidation, corrosion, distortion and sagging.

There are several methods for assessing and detecting the damage of the furnace tubes. All heater tubes should be inspected, preferably early in life, to establish base-line conditions for tube diameter, wall-thickness, microstructure, and metal hardness.

Figure 1. Pyrolysis furnaces in ethylene plant

FURNACE TUBE FAILURE

Tube failures result from progressive deterioration from a variety of deterioration mechanisms. Therefore, one needs to understand the active and potential mechanisms in a particular pyrolysis furnace in order to prevent them from causing a failure. Tube reliability not only requires an understanding of the mechanisms by which the tubes can fail, but also requires data on how the previous operating history has impacted tube life, predictions of deterioration rate, how the future operation will impact tube life, and finally, monitoring of operation sand deterioration to ensure the analyses and predictions are accurate and appropriate. Historically, inspection data gathered during outages assessed the immediate condition of the tubes with varying degrees of accuracy or success.

Creep is the primary cause of the furnace tube damage. It usually initiates within the tube wall some two-thirds of the way through from the outer surface, making it impossible to detect by in situ metallography [2]. This is opposite to boiler super heaters and headers where creep damage initiates at the outside surfaces, making it much easier to detect.

Creep elongation (also called stretching) occurs because of creep by the self-weight of the tube and the coke layer present in the tube and is influenced by temperature, the load carrying cross section of the tube, and the material used. A consequence of a high creep rate is the need to shut down the furnace and to shorten the coils (some end-users have lowered to bottom floor). Failures can occur if tubes are not shortened before they reached the heater floor (Figure 2). The coils are warped and bowed, resulting in higher tube stresses and creep rates.

During service, hard deposits of carbon (coke) build up on the inner wall of the tube, reducing heat transfer and restricting the flow of the hydrocarbon feedstock's. About every 20 to 60 days, the furnace must be taken off-line and "decoked" by burning out the accumulated carbon.

Carburization is the carbon enrichment and carbide formation in the tube material under influence of the presence of carbonaceous gases and high temperatures. This accelerates carbon diffusion in tube material, especially during the decoking period. Carburized material in the inner wall of the radiant tube has a higher thermal expansion coefficient and tends to increase in volume and place stresses on the tube. These thermal stresses make the tube more susceptible to creep failure [5]. The deposition of the coke at high temperature is generally inhibited by the presence of a Cr_2O_3 layer on the inner surface of the tube. When this film in present carbon diffusion into the tube is retarded. However, during decoking, the tube may be subjected to severe thermal shock that results in removal of the Cr_2O_3 layer, so the carburization attack increased [8]. Because of exposure of tube at elevated temperature, carbon diffusion could promote formation of continuous and/or separated carbides in grain boundary and matrix [1,7,8]. These carbides decrease the creep resistance and ductility at high temperature.

Figure 2. Pyrolysis furnace radiant zone - consequence of a high creep rate

Metal dusting is a catastrophic form of carburization that can result in rapid metal wastage in both ferritic and austenitic alloys. This damage mechanism typically has the appearance of localized pitting, or grooving, along the inner walls of pipe and tubes [8].

The ductile failure can be recognized by a bulge on the tube and a short longitudinal crack on top of the bulge. In the micro-structure creep voids can be observed between matrix and carbides [1].

The brittle fracture can be recognized by a long longitudinal crack which "ends" in a fork-like appearance. Sometimes, the cracks result in circumferential rupture or "windows" that fall out of the tube. The cracks can be many meters long, and many times, a thick coke layer is present inside the tube. In the micro-structure can be observed that the carbides have split. This is a marked difference to the ductile fracture and can be recognized easily [9].

Another failure mechanism is overheating, which results in local melting or overall melting of the tubes. Such an overheating can happen due to lack of flow, coke blockage or burner problems (flame impingement). Lack of flow can occur when inlet valves fail or in case of compressor problems.

Above 1100°C nitriding respectively internal nitride formation occurs from the outer diameter of the radiant tube (flue gas side). Nitrogen penetrates through the oxide and reacts with chromium by precipitation of nitrides. Due to nitriding the rough as-cast surface disappears and the surface becomes a smooth and glazed appearance [4]. The nitrides may cause spallation of the oxides. As a result a thick layer of oxides (up to 10 – 20 cm thick) can be found on the furnace floor. Sometimes, this is called oxide shedding.

Another form of elevated temperature degradation of austenitic stainless steel is sensitization. This caused by precipitation of chromium carbides preferentially at grain boundaries. The immediately adjacent chromium-depleted zone is susceptible to accelerated corrosion in some aqueous corrodents. Sensitization has little or no effect on mechanical properties but can lead severe inter granular corrosion in aggressive aqueous environments such as polythionic acid. Polythionic acid can form during downtime on equipment that has been even mildly corroded by hydrogen sulphide at elevated temperature. The iron sulphide corrosion product combines with air and moisture to form the acid and induces intergranular corrosion and cracking [4].

Erosion can be observed in 90 or 180 bends or in Y-pieces. The most accepted theory is that erosion is caused by hard coke particles during decoking. Some investigators believe that this erosion is caused by coke particles, which are present during normal operation. The remedy is to modify the decoking procedure, so that the coke is gasified instead of being spalled. Second remedy is to lower the gas velocity during decoke below 200 m/s. Third remedy is to apply "internally stepped fittings", which have been applied successfully on many occasions.

FURNACE TUBE INSPECTION

Inspecting furnace tube is sometimes not an easy task. Everyone is looking for inspection method or test equipment that will find cracks or leaks 100% of the time. There are a variety of methods of inspecting or testing furnace tubes.In assessing the state of furnace tubes we use an optimal combination of methods, as individual methods cannot detect any potential damage. Test methods which involve the removal of pipe from the furnace is the most expensive as it is necessary to remove the tube from furnace and then remove the pattern.

Visual inspection

On-stream visual inspection of visible flame patterns can indicate potential areas of concern. An erratic, unbalanced flame may be a sign of damaged swirl vanes, improper air/fuel mixture, coking on the burner tip or leaking tubes. An erratic flame may impinge on nearby tube walls, causing hot spots and areas of potential ruptures.

Structural components, such as tube supports, that are visible from inspection ports should be examined to ensure they are intact. Any external tube suspension systems and pre-load and compensating devices should also be subject to routine inspection.

Tubes should be inspected for bulges, sagging, bowing, localized discoloration or leakage. Hot spots may be the result of flame impingement. Tube misalignment may be caused by damaged supports, or supports that are preventing the thermal growth of the tube.

Refractory should be visually checked for cracking, spalling, erosion, and localized discoloration. Areas of damage should be monitored for high temperatures and identified for repair during the next planned outage. A visual examination of the external casing should be made to detect any hot spots. Infrared thermography was used to online monitoring of pyrolysis furnaces.

During planed downtime the tube coils should be inspected closely for bulging, bowing, sagging, splitting, scaling, corrosion, and deposits from fuel gas. Fittings may show signs of damage, distortion or corrosion. Internal inspection of tubes is limited to those types which have removable U-bend or plug type fittings. Remote examination may also be utilized, using a boroscope, video camera or other visual aids. Suitable record such as videotapes should be maintained.

Tube temperature monitoring

Tube failures are most commonly due to overheating. Therefore close attention must be paid to on-stream monitoring of tube temperatures. Routine recording of tube temperatures into a permanent record is crucial to enable the remaining safe life of the tubing and suitable inspection intervals to be established. There are two basic systems for tube temperature monitoring: contact tube- skin thermocouple and non-contact pyrometers. They serve a couple purposes. First, the thermocouples can alert to abnormal operation if temperatures dramatically change. Second, they provide a means to calculate and monitor remaining tube creep life. Strategic placement of the thermocouples is necessary so that the entire firebox can be reasonably monitored.

Malfunctioning burners or unbalanced firing of burners can create local hot zones in the firebox and lead to premature failures. In addition, tubes that historically operate hot due to their placement in the coil may need a thermocouple, especially if it represents the most severe service of the tubes.

Infrared thermal scanning of tubes helps fill the gaps created with the tube-skin thermocouples. Infrared scanning inspection can determine local tube metal temperatures in the areas not covered by the tube skin thermocouples. Generally, tube rupture occur in very local areas of overheat. Infrared scanning has proven effective in identifying localized “hot spots” before they cause a failure. A periodic scan of heaters is common practice although some heaters whose tubes are particularly prone to coke buildup may require more frequent scanning. Additionally, infrared scanning with non-contact pyrometers provides a means to check the accuracy of tube-skin thermocouples.

Thickness measurements

Ultrasonic thickness readings should be taken at specified locations on tube coils in the radiant section, accessible shock (shield) tubes in the convection sections and return bends. A recent technological advance in furnace tube inspection has seen the development of a multi-module pig which can increase the number of data points from the typical 200-300 to in excess of 300,000. The tool can be used to inspect both the convection and radiant sections. However, since it uses ultrasonic, the inside of the tubes must be cleaned prior to inspection.

Tube growth measurements

Tube coils and return bends should be gauged for bulging or creep growth and the history of tubes that have been replaced due to thermal growth should be kept. Thermal growth may occur when the tubes are subjected to localized short-term overheating, long-term high temperature exposure (creep), or localized thinning of the tube through corrosion or erosion.

The maximum limits of diametrical growth based on acceptable levels of creep must be established and readings checked against these limits. Special pre-set gauges can be used to quickly scan the length of a tube and a micrometer used to take precise measurements at pre-selected locations or areas of concern.

Inspection methods that are based on laser technology in recent years has experienced rapid growth. With the advent of laser measuring profilometry outer / inner diameter of the pipe, as well as elongation, is given a new dimension to overcome the disadvantages of an earlier measurement methods. Ability to accurately measure and record the growth of creep means that the condition of pipes can be measured from the first day.

Carburization assessment

Carburization - is the diffusion of elemental carbon into solid steel in contact with a carboniferous material at high temperature. This results in a brittle material. Austenitic tubes are essentially nonmagnetic. Carburized areas of the tubes become magnetic, and if these areas are large, they can be detected with a magnet. A magnet on a string dropped down a tube will indicate areas that are *magnetic but will not indicate the depth of carburization. An eddy current instrument (Hall Effect hand held probe) called a magneto-scope should be used to build up a history of magneto-scope measurements. Any tube that indicates higher magneto-scope readings in any region should be checked by dye penetrant on the O.D. for cracking. Radiography should be carried out on the region to determine the condition of the I.D.*

Radiography

Radiography may be used to inspect weldments, tubes, and return bends etc. It will provide evidence of wall thinning, deposits, pitting, cracking and internal obstructions etc. In circular heaters the film can be placed behind each set of tubes or return bends at a given elevation, and the source can be located in the center. One panoramic exposure can then be taken that includes all of the tubes.

When radiographing a tube to determine if corrosion, deposits or coke is present, it is important to remember that these will usually occur on the fire side of the tube, as this is the hottest side of the tube. If a radiograph is taken on a horizontal tube, the film should be placed as close to the horizontal plane as is practical. The resulting film will show the profile of the fire side of the tube wall and the opposite side furthest from the source of heat.

Hardness measurements

Hardness testers -mechanical and electronic hardness testers can be used to determine the hardness of base metal, welds, and heat-affected zones. Electronic testers must be used with extreme care on thin materials or erroneous readings may be obtained. Hardness tests should only be specified only after it has been determined that the base material is suitable; as some materials (i.e. carburized, cast materials) may well be damaged if hardness readings are taken.

Hardness considerably increases with the extent of degradation, compared with virgin material. There is a relation between carburization and hardness, and electrical resistivity and carburization, so the electrical resistivity is inversely proportional to the hardness [6].

Metallurgical analysis and mechanical testing

It may be necessary to remove samples to assess the mechanical and metallurgical integrity of furnace components that are approaching their design life and cannot be assessed in place due to the design (i.e. finned tubes), or when inspection results indicate that sample removal is required to enable the overall condition of the furnace to be verified. Metallurgical considerations for sample removal would include: suspected high temperature creep damage, sensitization, carburization, decarburization, spherodization, oxidation, embrittlement, etc. The investigation included tensile tests, optical microscopy, scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and X-ray diffraction (XRD) analysis.

Scale/deposits- Samples of surface scale and deposits can be analyzed to determine composition, source of contamination and provide an indication of the degree of overheating.

In site metallography- provides metallurgical information to check for material deterioration, creep damage etc., without destroying its function.

Analyses of a pyrolysis furnace tube microstructure show that essential changes in material structure and properties appear during the operation at high temperatures. Uncontrolled carburization process result in coke deposits on tube causing heat stresses. Therefore, but also due to material creep, radial micro-cracks and fracture appear [5]. The fracture propagation is along the grain boundary where carbides are extracted in chains [7]. Initial austenitic structure has changed its characteristic in some places appearance of delta ferrite formation and sigma phase, which reduce material ductility together with the carbides inside and along the grain boundaries.

Pressure test

Before the furnace is returned to operation, a pressure test on the tube coils will reveal any leakage not apparent from a visual inspection. All pressure tests should be performed in accordance with a written procedure which includes the safety precautions to be taken, test pressure and temperature, how water will be drained from vertical coils etc. A full temperature compensated hydrostatic test is required when welded repairs to the pressure envelope have been made. When a full *hydrostatic test is not practical, a pneumatic test or alternative testing may be conducted.*

CONCLUSION

Process furnaces are critical components in the oil and petrochemical industry, and the process equipment damage assessments have great importance for providing a safe, highly effective and long-term work. Traditional means of monitoring these high temperature vessels have frequently been more art than science, often relying on highly subjective analyses and/or frequently inaccurate thermocouple data. Time interval replacement of tubes is essential in costs reducing and productivity maintenance in the process industry.

Heater reliability often depends on periodic internal inspections and routine, on-stream monitoring/inspection. These techniques of tubes inspection provide adequate assistance in collecting data about their condition. Typical on-stream inspection programs incorporate visual examination of the firebox, external visual examination of casing and components, infrared examination of tubes and heater casing, and monitoring of tube-skin thermo couples. Before the inspection, the tools needed for inspection should be checked for availability, proper working condition, and accuracy.

External and internal inspections should be scheduled periodically considering the age of equipment, conditions of operation, type of equipment, kind of fuels, previous inspection result, etc. However, the length of time between internal inspections should consider the historic and predicted deterioration rates for components (including the impact of any process change), the historic inspection findings, the results of on-stream monitoring/inspection, previous maintenance activities and their quality.

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