Advanced NDTs for Inspection of Catalyst Tubes of Reformer Furnace

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Abstract

The Reformer tubes used in the refining, petrochemical and fertilizer industries are manufactured by the centrifugal casting process of heat-resistant austenitic alloys such as HK-40, HP-40, and HP-Niobium modified materials. These tubes are prone to various degradation mechanisms like creep, hydrogen attack, corrosion, fatigue etc and the useful life of these tubes is largely dependent on operation and maintenance. Also, as these tubes are operated at severe conditions, the determination of the serviceability of these tubes beyond their design life of 100,000 operating hours is of vital importance. A range of NDTs are presently available which provides the opportunity to improve the reliable service life of reformer tubes. Thus, rather than to remove tubes from service for sectioning and metallurgical examination at every plant turnaround, it is advantageous to use NDE techniques to screen the tube condition for environmental damages such as creep.

Proper determination of tube condition and its ultimate life requires specific in-situ examinations. Reformer tube condition can currently be assessed in-situ by qualitative NDE assessment using various techniques like Diametrical Growth Measurement (diameter change with creep in some cases), Wall Thickness Measurement (apparent decrease in wall thickness with creep), Replication (final stages of creep damage; i.e., macro-cracking), Radiography (final stages of creep damage; i.e., macro-cracking), Eddy Current Testing (responds to chromium migration due to overheating and conductivity changes) and Ultrasonic Testing (responds to attenuation and scattering).

Extensive trials have been conducted to determine the viability and optimization of the various techniques and it has been established that the tube condition cannot be conclusively determined by one stand-alone technique, but by effective combination of multiple techniques depending on the degree of damage. One such combined advanced NDE technique is ‘H’ SCAN Technology, which is now widely used for damage assessment of Reformer tubes. Another breakthrough technology in this field is Laser Optic Tube Inspection System (LOTIS). The advantages and disadvantages of each technique, when compared against each other, reduces the occurrence of false calls, improves tube condition assessment and can increase overall furnace reliability.

Introduction

In Petroleum Refineries and Petrochemical Plants, hydrogen is essential for hydro-cracking, hydro-finishing and other hydro-treating at various stages of hydrocarbon processing. Hydrogen generation unit of a petroleum refining plant is of paramount importance. The reformer furnace of a hydrogen generation unit is one of the most critical static equipment as it operates at very high temperature in hydrogen atmosphere. Exposure to high temperature and hydrogen environment makes reformer catalyst tubes vulnerable to various degradation processes. The catalyst tubes of reformer furnaces are manufactured by the centrifugal casting process of heat-resistant austenitic
alloys such as HK-40, HP-40, and HP-Niobium modified materials. Most of the manufacturers design catalyst tube considering a service life of 1,00,000 hours. Chronological development of reformer alloys along with their chemical composition had been taking place from time to time and with advent of third generation (HP-Nb modified) and fourth generation (HP Micro alloyed) metallurgical advancement, it is now possible to extend the catalyst tube life if tube retirement is based on condition based assessment rather than time-based assessment. Therefore, non destructive testing of catalyst tubes becomes necessary for timely identification of different types of damages caused by high temperature and hydrogen atmosphere. Qualitative NDE assessment and operation within design limit can enhance the catalyst tube life beyond normal design life of 1,00,000 operating hours.

Reformer tube : Damage Mechanisms

The major in-service damage mechanisms prevalent in the centrifugally cast Reformer tubes are as follows:

1) **Creep**

At elevated temperatures and stresses much less than the high temperature yield stress metals undergo permanent plastic deformation called creep. There exists a region of extensive plastic deformation where the strain rate remains more or less constant before as a final accelerated deformation leading to failure. It is this constant strain rate values that are considered for materials in the components design. Stress rupture signifies creep under conditions of elevated temperatures or high stresses within a very short time such as the conditions encountered in access of flame impingement. Damage normally starts at the centre of the tube thickness and, due to operating temperature and pressure, develops to the inner surface. The void further joins to form micro-cracks followed by macro-cracks. The typical stages of creep damage in Reformer tubes are shown in Fig # 1. A case of reformer tube rupture due to creep failure is shown in Fig # 2.

2) **Hydrogen attack/ fissuring**

Steels exposed to high temperature high pressure hydrogen for days or months lose its strength and ductility suddenly. This type of damage is called hydrogen attack. Hydrogen attack is irreversible damage and occurs at high temperature. In hydrogen attack of steel, absorbed hydrogen reacts internally with carbides to produce methane bubbles along grain boundaries; these bubbles subsequently grow and merge to form fissures. Failures by hydrogen attack are characterized by decarburization and fissuring at grain boundaries or by bubbles in the metal matrix. This type of hydrogen damage is experienced in steels that are subjected to elevated temperature in chemical refinery plant equipments hydrogen and hydrogen-hydrocarbon streams at high pressure and high temperature. The severity of hydrogen attack depends on temperature, hydrogen partial pressure, stress level, exposure time and steel composition. Additions of chromium and Molybdenum to the steel composition improve the resistance to hydrogen attack.

3) **Hydrogen blistering**

At high temperatures in hydrogen environment, the hydrogen molecules dissociate into atomic hydrogen and the reversible reaction is in dynamic equilibrium. In high temperature operation the hydrogen diffusing through the steel causes blistering. If the steel contains voids, laminations or inclusion, the atomic hydrogen cannot pass through these defects. The molecular hydrogen (gas) is formed at metal / void or inclusion inter-face which is entrapped within these defects. The gas being compressible, over a period of time sufficient pressure is generated to protect the metal at these discontinuities. In extreme cases, externally visible blisters are formed.
4) **Hydrogen Embrittlement**
When high strength steel containing hydrogen is stressed in tension, even if the applied stress is less than the yield strength, it may fail pre-maturely in a brittle manner. This type of hydrogen damage occurs most often in high strength steels, primarily quenched and tempered steels and precipitation-hardened steels. The presence of hydrogen in steel reduces the tensile ductility and causes premature failure under static load that depends on stress and time. This phenomenon is known as hydrogen embrittlement.

5) **Metal Dusting**
Metal Dusting is the term used to describe the catastrophic degradation of metal in carbonaceous gases at elevated temperatures, usually in the range 450° to 900° C, in which metal surface rapidly becomes severely pitted. General metal wastage has also been observed. The term is derived from the appearance of the pits, which often contain a dust of loose, magnetic corrosion product of graphite, metal carbides and oxides.

**Inspection Techniques**

The Reformer tubes are subjected to severe temperature and pressure conditions during operation and hence the monitoring of the condition of the tubes is of utmost importance. Since the deterioration of the tubes is largely dependent on the operating temperatures, the fluctuations in the operating conditions, number of start-up/shutdowns etc, regular monitoring of skin temperatures of tubes using infrared thermometers is carried out. Infrared thermography helps in identifying the specific tubes running with high skin temperature and also provides an illustrated profile of the furnace box depicting the zone of concern.

A series of Non Destructive Testing methods are generally employed for inspection and health assessment of Hydrogen Reformer tubes since no single technique can successfully detect all types of damage mechanisms prevalent in the Reformer tubes. During shutdown, the various NDT methods that are involved for assessment of reformer tubes are as follows:

- **Visual examination**: for surface blisters, surface profile, roughness etc.
- **Radiography**: for ascertaining cracks/defects, found with other assessment methods. A radiograph showing multiple fissures in a failed tube is shown in Fig # 3.
- **Diametrical Growth Measurement**: it is used for detection of creep damage.
- **Wall Thickness Measurement**: it is used for measuring thickness loss due to metal dusting or apparent thickness loss due to creep.
- **Replication**: Replica technique is one of the methods used for study of micro-structural changes and the extent and nature of damage/defects. The method being limited to study of the exposed surface, replica technique has comparatively limited used in the study of hydrogen related damage.
- **Eddy Current Testing**: The technique relies on changes in electric circuit conditions; the circuit being the instrumentation, cables, sensing coil, and the item under test. As the mechanical properties of the test materials change, a change in overall circuit impedance occurs, which is displayed on an oscilloscope. By monitoring these changes, it can be inferred that creep damage is present, based on observation of the signal parameters in comparison to similar changes that occurred on known creep-damaged materials.
Automated Ultrasonic Testing (AUS): It is well known that the creep damage in materials progresses with void nucleation, void growth, void delineation and link up to form micro crack and subsequently macro cracking. Ultrasonic signal parameters are essentially depend upon the properties and state of the medium through which they pass through. Just as coarse and fine-grained materials interact differently with Ultrasonic waves; presence voids attenuate the ultrasonic signals to varying extent depending on the void density and distribution. The principle of Automated Ultrasonic scanning is shown in Fig # 4. By studying the levels of attenuation one can characterize the voids present within the material. An Automated Ultrasonic Scanning technique precisely estimates the attenuation levels of Ultrasonic signals in centrifugally cast Catalyst tubes of Hydrogen reformer unit and interprets the results qualitatively with respect to creep void accumulation. Fig # 5 shows AUS in progress in one of the Reformer furnaces.

Laser Optic Tube Inspection System (LOTIS): LOTIS is used to take a large number of inside and outside tube diameter measurements and build up a picture of the creep damage that inevitably occurs during operation of the reformer furnace. The LOTIS technology utilizes unique laser probes. Experience with this technique has been identified with many benefits like rapid, accurate measurement of tube diameter, determination of creep damage, pictorial display of data. LOTIS can be planned to coincide with catalyst loading work.

'H' SCAN® Technology: a combination of a set of NDT methods to complement the lacuna of the various NDTs when performed alone. The 'H' SCAN technology performs Ultrasonic attenuation, Eddy Current, Dimentional measurements and wall thickness data through a air operated scanning head linked to imaging systems and softwares which analyses the data and categorizes the scanned tubes into five grades as per their degree of damage. Fig # 7 shows the scanning of a reformer tube by H-Scan probes.

For all the technologies adopted for health assessment of Reformer tubes, it is important to have the base-data to ascertain the degree of deterioration during a particular period of operation. The base data also helps in the decision making process regarding the servicing of a particular tube for the future runlength of the furnace.

Conclusion

The reformer tubes in operation are prone to various degradation mechanisms and the useful life of these tubes is largely dependent on operation and maintenance. The remaining life of these tubes can be assessed by utilizing a combination of different inspection techniques. Side by side, it is equally important to restrict the operating parameters within the design operation window.

Fig # 1 : Stages of creep damage in reformer tubes
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