Reactor effluent air cooler safety through design

Quality-controlled replacement of carbon steel with Duplex 2205 for revamps can increase the service life and reliability of the REAC in the high-pressure

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In hydroprocessing units, the reactor effluent cooler (REAC) is one of the most vital pieces of equipment, and any hindrance to its smooth operation immediately impacts the whole high-pressure loop. Older REAC designs used carbon steel, but these required low concentrations of ammonium bisulphide and/or polysulphide sulphide injection together with frequent and thorough inspections. As feeds in most heavy oil hydroprocessing service have become more laden with sulphur and nitrogen, the concentrations of ammonium bisulphide with economic levels of water injection have risen to a point where carbon steel tubes have routinely been substituted by alloy tubing.

Duplex 2205 and Alloy 825 are used, with the former being very popular because it is relatively less expensive. Initially, there were several problems associated with Duplex 2205, which were a result of poor fabrication techniques. These included a rapid cooling rate associated with thick header boxes, which could result in high ferrite and thus poor corrosion resistance; welding of thick tubes to tube sheets with joint leaks; and lack of control of welding, resulting in high hardness and thus susceptibility to sulphide stress cracking. Many of these initial problems seem to have been overcome. However, problems persist around the REAC, primarily because of a lack of attention to detail and not adhering to licensor specifications. In this article, we will illustrate real REAC problems from recent projects and consider the remedies that were recommended

Background

In the hydroprocessing industry, the REAC is one of the most important components in the high-pressure recycle gas loop. It typically provides the final cooling solution before separating the vapour (recycle gas) from the oil effluent and the sour water. The outlet temperature directly impacts recycle gas molecular weight as larger hydrocarbon molecules drop out of the vapour phase. The same mechanism also affects the hydrogen partial pressure, which directly impacts reactor catalyst life. The importance of this piece of high-pressure equipment cannot be overstated. However, operating under high pressures and low temperatures can bring a host of issues into the equation, not the least of which includes ammonium bisulphide (NH_4HS) and ammonium chloride (NH_4Cl) precipitation (leading to pressure drop build-up), corrosion and/or erosion-corrosion. Some refiners have also experienced cracking in REAC welds, leading to fires, and loss of both time and money.

Tube metallurgy has a huge impact on a REAC's life expectancy. Materials currently used in REAC systems include carbon steel, Type 400 series stainless steels, Type 300 series stainless steels, duplex stainless steel Alloys 3RE60 and 2205, Alloy 800, Alloy 825, Alloy 625 and Alloy C-276. Early refiners used carbon steel and this was found to be effective with NH_4HS concentrations up to 3 wt%. As sour opportunity crudes became available, the resulting NH_4HS crept up into the double digits. In cases where the resulting NH_4HS was between 3-8 wt%, polysulphide injection was a very cost-effective solution for the continued use of carbon steel (especially for revamps). However, over time, the persistent plugging/operation problems, frequency of inspection and the foul smell of the polysulphide liquid greatly diminished its use. Increasingly sour feeds demanded more corrosion-resistant materials such as nickel-based Alloys 625, 800 and 825. Capable of handling up to 15 wt% NH_4HS, Alloy 825's corrosion resistance is normally matched by an equally hefty price tag. As the cost of materials continued to rise, a more economical alternative with comparable protection against corrosion was sought.

Duplex stainless steels are often successfully used in these systems because they offer advantages from both the ferritic and austenitic stainless steel families. They are often cost effective due to their higher strength and reduced alloy element content compared to other higher alloys (up to one-third the cost of Alloy 825). However, since these materials consist of dual-phase microstructure, heat-treating, fabrication and welding techniques need to be carefully reviewed and monitored to assure that the balanced microstructure is not compromised. In the past, Duplex 3RE60 was used, but it had inferior corrosion resistance and toughness at the welds (it is no longer available). The most commonly used grade today is Duplex 2205.

Early implementations of duplex REACs failed to show significant reliability improvements, and a few units failed by hydrogen embrittlement cracking or sulphide stress cracking (SSC). Advancements in steel manufacturing have minimised microstructural deterioration during fabrication. Weld procedures and practices have been developed to assure balanced ferrite and austenite content, thereby improving reliability. API TR 938C provides guidance on materials and fabrication practices to achieve good corrosion resistance in duplex stainless steels.

Case studies

Many of the reported incidents involving Duplex 2205 REAC failure have a common thread: pressures greater than 1000 psig and a NH_4HS concentration of 6 wt% or greater. The following two recent case studies highlight these conditions.

A licensee in Asia ("Company A") had a carbon steel REAC running for a number of years. An expansion of the unit required a REAC metallurgy upgrade to Duplex 2205. The design pressure of the REAC was ~2400 psig and the NH_4HS concentration was expected to be 5 wt% during the modelling phase. A new Duplex 2205 REAC was installed and ran without issue for about two years, then fire erupted due to REAC failure, and nearby equipment and piping were damaged. Cracks were observed on the weld joints between the top plate and tube sheet, as well as the bottom plate and tube sheet of the floating header. Fin tubes were deformed and the walkway was nearly unusable. An investigation was commissioned to find the root cause of the REAC failure. The investigation discovered that during the REAC fabrication, Charpy impact testing was conducted at 0°C instead of -40°C (as specified by CLG). This oversight led to inadequate toughness and low ductility for the welds as well as less than favourable microstructural phase balance. Hardness values in the heat-affected zones (HAZ) and at the weld of failed specimens were higher than those recommended (in the range of 313-359 HV10 vs 310 HV10 maximum). As a result, CLG concluded that REAC failure in this case was due to sulphide stress cracking (SSC).

Another licensee based in the US ("Company B") had a two-stage hydrocracker and hydrotreater ready for startup. The unit required a Duplex 2205 REAC. The design pressure of the REAC was ~2400 psig and the NH_4HS concentration was expected to be 8 wt% based on modelling. During initial startup, a decision was made to skip the high-pressure tightness testing. A fire erupted from cracks formed in the REAC outlet temperature indicator thermowells in two separate trains. These cracks were found to be a result of improper manufacturing practices (of the failed duplex material) and would have been detected during a high-pressure tightness test. By not following standard operation practices, the unit startup was delayed.

REAC safety through design

Issues that plague the industry's REACs can be mitigated or eliminated altogether by considering "Safety Through Design". In preparing a basic engineering package for licensees, CLG highlights certain areas and design considerations that are considered strong recommendations. These considerations include:

- Using balanced, symmetrical piping
- Limiting tube velocities based on metallurgy, NH_4HS concentration and H_2S partial pressure
- Specifying fabrication and welding guidelines for Duplex 2205 above and beyond those specified in API TR 938C

• Using single-point water injection instead of multi-point water injection.

Symmetrical piping for REAC inlet tubes is critical for reactor effluent. It is impossible to implement any type of flow control for two-phase flow, so the use of symmetrical piping will ideally provide even distribution of gas and liquid phases as it enters the air cooler. The danger of uneven phase distribution is that tubes favouring vapour will have more NH_4HS deposits, and tubes favouring liquid will have more of the injection water. These deposits will eventually plug the tubes and increase the rate of corrosion. Consequently, unplugged tubes will see higher than acceptable velocities, increasing the rate of erosion/corrosion. It is possible for piping to be symmetrical and still be unbalanced. Balanced headers require additional splits, but will prevent flow that follows the "path of least resistance".

During basic engineering, CLG specifies tube velocity limitations based on the tube metallurgy selected along with NH_4HS concentration:

• For carbon steel tubes and piping with less than 3 wt% NH_4HS, 10-20 ft/s is allowed, with 15 ft/s preferred

• For 2205 duplex stainless steel tubes and piping with 3-12 wt% NH_4HS, 10-30 ft/s is allowed, with 25 ft/s preferred

• For Alloy 825 tubes and piping with up to 15 wt% NH_4HS, 10-40 ft/s is allowed, with 35 ft/s preferred.

In all cases, tube velocities falling below 10 ft/s become quite hazardous, as phase separation and corrosion can result.

For the industrial use of Duplex 2205, API TR 938C gives a great starting point for fabrication and welding guidelines. CLG has crafted a standard specification that addresses certain areas in more depth, and creates greater accountability for both the fabricator and the welder. For example, CLG specifies a maximum hardness rating of 310 HV10 versus API's requirement of 320 HV10. There is also tighter control of weld consumable and filler metals. Qualifications for Weld Procedure Specifications (WPS) and Procedure Qualification Record (PQR) are also much more stringent. As the two case studies illustrate, Duplex 2205 REAC failure can be attributed to not respecting the guidelines specific to duplex material.

One final design consideration is whether to use single- or multi-point water injection before the REAC. With the numerous valves involved in a multi-point water injection system, water management is difficult. Even with symmetrical piping, a multi-point water injection system may have some tubes favouring more water than others. This scenario can be dangerous, as some tube temperatures fall below the NH_4HS precipitation temperature. Single-point water injection ensures that the global water requirement is met from the start, well before the effluent splits into their separate headers (the injection point is typically 10 pipe diameters upstream of the split). Another benefit of single-point injection is that the recycle gas compressor spill back line can be positioned downstream of the injection point so that it is washed with injection water. This setup minimises NH_4Cl and NH_4HS formation in the dead-leg piping.

Summary

The combination of high pressures and corrosive environments can spell disaster for REACs in the refining industry. Fortunately, measures such as using balanced symmetrical inlet piping, limiting tube velocities based on metallurgy and NH_4HS concentration, working with suppliers and welders who have good-quality control with Duplex 2205, and the use of single-point water injection can increase the service life and reliability of the most important air cooler in the high-pressure loop.

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