Root Cause Analysis of Failure in Hot and Cold Mixing Point in Hydrogen Generation Unit (HGU)due to Thermal Fatigue Phenonmenon

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ABSTRACT

In a Process unit there are several streams that are exchanging heat to optimize the unit operation. In the HGU at IOCL, Guwahati refinery repetitive failures were observed in a 2" Ö, SS 304 pipe at this hot and cold mixing point. The investigation revealed that the two streams were handling fluid at a temperature of 40°C and 160°C, the difference being ≈ 120°C. These huge temperature differences lead to thermal gradient across the wall thickness of the pipe and also along the length of the pipe surface in the flow direction. The inner surface of the pipe seeing a higher temperature than the outer surface and therefore more expansion at inner surface. Due to this thermal fatigue phenomenon and hindered expansion severe stresses were observed at the inner surface of pipe leading to crack initiation and further propagation across the wall thickness. As a temporary measure the joint was replaced with identical pipe with higher thickness (schedule), and as a permanent solution it was suggested to replace the mixing point with an injection "Quill" design to avert the huge thermal gradient

Key words: Thermal gradient, thermal fatigue, Quill , process mixing point

1.0 INTRODUCTION

The reliability of a process unit operation is to a large extent dependent on the reliability of its mechanical equipments. In this case, the reliability of the process equipments like column, vessels, heat exchangers, piping, pumps, compressors are of paramount importance for safe and reliable operation and the profitability of the unit operation. The outage of hydrogen generation unit due to failures by leakage in the process pipeline will not only lead to upset in the unit operation but also cause indirect throughput loss / shutdown of its dependent units like Hydro treater unit and MS-quality up gradation units.

In a process plant where several streams are exchanging heat & mass, a sound engineering design will help to minimize, if not completely eliminate, the failures due to large variations in the temperature profiles of these process streams. This paper describes about the repetitive failures experienced in the 2" Ö, SS 304 pipe at hot and cold mixing point. Temporary measures under taken and permanent solution suggested to combat this chronic failure are also discussed in the paper.

2.0 BRIEF PROCESS DESCRIPTION OF HGU

The HGU at Guwahati Refinery (GR) is a 10000 TPA (1250 KG/HR) plant which produces hydrogen of 99.9% purity. This hydrogen is primarily used in hydro-treater unit and MSQ unit for producing diesel, ATF, MS and kerosene. The process licensor is M/s KTI-BV, Netherlands. The feed is light Naphtha and off gas.

The Hydrogen Unit is divided into the following sections:

1) Feed preheat.

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2) Hydrogenation.
3) De-sulphurisation and de-chlorination.
4) Pre reforming.
5) Reforming.
6) Heat recovery.
7) High temperature shift conversion.
8) Low temperature shift conversion.
9) Boiler feed water conditioning and steam generation system.
10) Pressure swing adsorption system (PSA).

The feed light naphtha from CDU (crude distillation unit) and off gas from LRU (LPG recovery unit) is preheated to 250°C in the preheat section and sent to hydrogenation section. LRU off gases contain significant amount of olefins and light naphtha contains mercaptans as well as traces amount of heavy metals such as arsenic, lead, vanadium, copper, which are catalyst poison. In the hydrogenator, olefins are saturated. The mecaptans are converted to hydrogen sulfide. The impurities are absorbed on the hydrogenator catalyst. For hydrogenation Co-Mo catalyst is used.

The feed is then sent to desulfurization and de-chlorination section for chlorides and sulfur removal in the sulfur absorbers containing bed of zinc oxide with top layer as chlorine guard. The feed is then sent to pre-reformer section where the de-sulfurised feed is mixed with controlled quantity of steam so as to have feed to steam ratio of 2.5 kg/kg. It is then heated to 450°C and routed to pre-reformer. Hydrocarbons in the presence of steam react over a nickel based catalyst to form an equilibrium mixture of methane, carbon dioxide, carbon monoxide and hydrogen.

$C_2H_6 + 2H_2O \Rightarrow 2CO + 4H_2$ (Endothermic)

$CH_4 + H_2O \Leftrightarrow CO + 3H_2$ (Endothermic)

$CO + H_2O \Leftrightarrow CO_2 + H_2$ (Exothermic)

Pre-reformer effluent goes to reformer section where it is mixed with additional quantity of steam and then superheated up to 630 °C . This preheated feed then enters reformer furnace at top section through inlet pigtails connected to 36 nos. of tubes. The reformer is operated at steam to carbon ratio of 2.8 in design feed case.

The conversion of methane with steam to CO and H_2 is strongly favored by high temperature, low pressure and high steam ratios in the presence of nickel based catalyst. Conversion reaction takes place in tubes in presence of the catalyst. The normal reformer outlet temperature is 850 °C.

$CH_4 + H_2O \Leftrightarrow CO + 3H_2$

$CO + H_2O \Leftrightarrow CO_2 + H_2$

The process gas is then sent to High temperature (HT) and low temperature (LT) shift conversion section. In the LT section the process gas passes through a series of reactors, vessel V-07 (hot condensate separator) and V-08(cold condensate separator) and exchangers and further to pressure swing adsorber (PSA) section for purifying the final hydrogen gas to 99.9 % purity.

2.1 Location of the failed mixing point:

The dia. 2", SS-304 hot and cold mixing point, is located in the down stream of vessels V-07 (hot condensate vessel) and V-08 (cold condensate vessel). The temperatures of the streams are 160°C and 40°C respectively. The isometric sketch below (Fig. 1) shows the layout of the piping configuration and the location of the failed mixing point.

2.2 Material of construction (MOC) and operating parameters:

Line size : dia. 2"

MOC of pipe : ASTM A-312 Gr, TP 304, schedule 40S (originally)

Operating temperature : 40°C (cold stream), 160 °C (hot stream)

Operating pressure : 21.8 kg/cm^2 & 21.2 kg/cm^2 in the hot & cold condensate lines respectively.

Service : Hot & cold condensates (From V-07 & V-08 vessels respectively).

Fluid velocities of the hot, cold & mixed

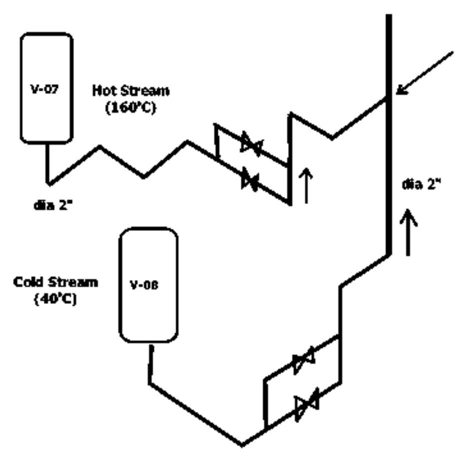

Fig. 1 : Isometric Sketch of Hot and Cold Mixing Point, showing the failed location

condensate streams are 0.33 m/s, 0.42 m/s & 0.75 m/s respectively with flow of $2.44m^3/hr$, $3.09m^3/hr$ and $5.53m^3/hr$ respectively.

2.3 Inspection history and repair jobs undertaken

The hydrogen generation unit (HGU) at IOCL, Guwahati Refinery was commi-ssioned in the year 2002. In May 2006, leakage was noticed for the first time since commissioning of the unit at a mixing 'Tee' due to cracking of dia. 2" cold header pipe located opposite to hot condensate entry point (at 90°). Preliminary inspection of the leaked 'Tee' was carried out by scanning with an ultrasonic thickness gauging meter of "panametrics make" to identify loss in metal wall thickness of the cold header pipe due to corrosion/erosion. There was no wall thickness loss in the Tee at any location. The external surface of the cracked 'Tee' was also inspected by dye-penetrant testing (DP test). Surface cracks were noticed near the leaked location.

Since this was the first incidence of cracking, the original angle of 90° connection (Tee joint) was changed to 45° connection ('Y' joint) in June'06 turnaround (Fig.2). A reinforcing pad was provided at the 'Y' joint for strengthening the weld joint. The original dia. 2" Ô, schedule 40S (3.91mm thickness) pipe at branch and main header was replaced with higher schedule pipe, i.e. schedule 80S (5.54 mm thick). Thus by increasing the weld area in a 45° connection along with reinforcement pad than a 90° connection, the thermal stresses were minimized.

Welding of SS304 pipe and RF pad was carried out after joint preparation with E-308 electrode. After completing the replacement job of the failed 'Tee' joint with a 45° 'Y' joint, final DP-testing of the reinforcement (RF) pad weld joint and radiographic inspection of butt joints (4 nos) was carried out. The condition was found satisfactory. As an improve-ment in the design it was recommended to change this welded 'Y' joint at the mixing point, with a dia. 2" Ô, schedule 160 (8.74mm thick), SS304 latrolet in the next opportunity. This forged latrolet will reduce the stress concentration produced at the mixing 'Y' joint.

In July 2008, the mixing 'Y' joint failed once again after staying in operation for approximately 2 years. This time the leak was noticed from the weld joint of reinforcement pad to the 2" dia pipe in the hot and cold mixing point (see Figs. 3 & 4). Thickness survey of the portion in and around the cracked location did not reveal any corrosion/ metal loss.

As the recommended latrolet was not available, the cracked mixing 'Y' joint was replaced with an available equal Tee of dia.

Fig. 2 : Photograph of Replaced mixing point modified to 'Y' joint, DP tested after replacement in 2006

Fig. 3 : Photograph of Leaking portion of the mixing 'Y' joint at RF pad weld joint in 2008

Fig. 4 :Photograph of Hot & cold condensate mixing Tee point after insulation removal

2", schedule 160 (8.72 mm thick) confirming to SS 304 material. The butt welds (3 nos) were inspected using radiography and were found satisfactory. An RF pad was provided at the 'Tee' portion for strengthening. The RF pad welding was DP tested, no significant indications were observed.

The replaced failed 'Y' mixing joint was inspected using a remote visual inspection video scope (RVI) to see the condition of the inner surface of the pipe/'Y' weld joint. Multiple surface cracks were noticed in the weld joint between the main header and branch pipe ('Y' joint) and also on the pipe surface upstream and down stream of the flow direction. (See Figs. 5 & 6). These cracks were both linear and branched cracks.

The second time failure implies that the 'Y' joint design was not sufficient to accommodate the thermal stresses generated at the mixing point. This mixing point was identified as "critical injection point" for close monitoring during operation and maintenance shutdowns. For a permanent solution to this chronic cracking problem, experiences of other refineries, API (American petroleum institute) committee reports and API standards were surveyed. Based on this an "injection Quill" was recommended for installation at the mixing point in Dec 2008. The design details of the quill were worked out and the engineering design was approved through our engineering department in 2009.

In Aug-2010 the unit was shut down for maintenance purpose. Seeing the criticality of this mixing point, weld joints and adjacent one feet region on all the three sides of the Tee portion was inspected by dye-penetrant test and ultrasonic flaw detection (UFD). Linear indications (micro cracks) were observed on the inner surface at the 'Tee' point at reinforcement pad location and inner pipe surface downstream of flow direction. As the 'Quill' was not available, this 'Tee' joint was replaced with SS304 schedule 160 pipe without reinforcement pad. It was realized that the reinforcement pad was also adding to the stress concentration instead of acting as strengthening to the 'Y'/Tee weld joint. Welding was carried out using E 308 electrode. D.P. testing of 'Tee' joint and radiography of butt weld joints were carried out to ensure weld soundness.

3.0 DISCUSSION AND ANALYSIS

From the chronological sequence of failures mentioned above, it is very clear that the problematic zone is the mixing Tee/'Y' point only. No leakages or failures were noticed in the straight pipe or elbows in either of the hot or cold condensate circuit. This also confirms that there is no corrosion/failure mechanism operating from process side i.e from the condensate flowing inside these pipes.

In the first instance of failure i.e May 2006 the hot condensate was entering the cold condensate pipe at 90° (Tee configuration at the mixing point). Therefore the hot condensate at 160°C was directly impinging the cold condensate pipe wall opposite to the flow direction. A hot spot was formed at this localized impingement spot where the temperatures experienced were in the order of 120 -160° C. This caused localized thermal stresses causing leakage over a period of time. It was thought that changing the 90° flow to an

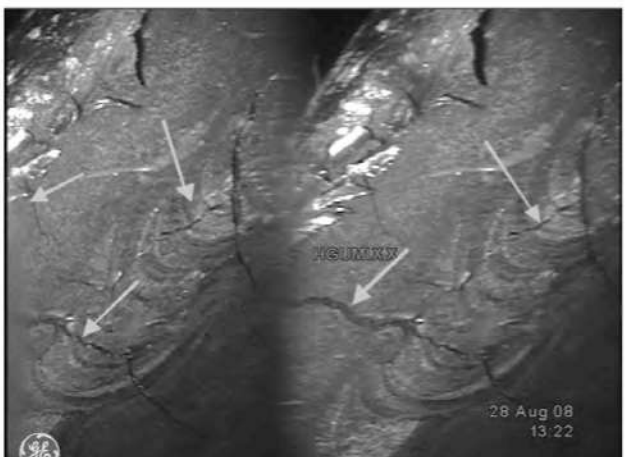

Fig. 5 : Photograph of Cracks noticed using remote visual inspection (RVI) instrument on the inner pipe surface at the mixing Tee location

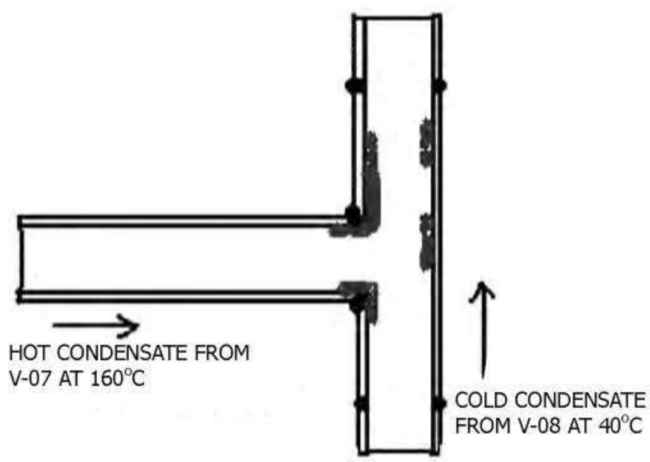

Fig. 6 : Sketch showing portion cracked by thermal fatigue

angular flow (45° to the cold condensate line) would eliminate the problem as there will be uniform mixing after the design change. Also the weld area in a 45° joint being greater than 90° would distribute the stresses over this area thereby reducing the overall stress. An additional RF pad was provided to further strengthen the 45° 'Y' joint.

However, in July 2008, leakage occurred once again in this modified 45° design, this time from the RF pad weld joint. This indicates that the above design was not adequate to handle the thermal stresses generated at the mixing point. It was also understood that the RF pad was actually increasing the thermal stress by acting as stress raiser point. The extensive surface cracks observed in the failed sample inner surface by RVI instrument indicates that the expansion of the inner surface seeing high temperatures of the order of 120-160 ° C is being restricted in the longitudinal and thickness direction by the adjacent metal pipe experiencing lower temperatures. The RF pad is further restricting this free expansion and increasing the thermal stresses.

Because of the small size of pipe line (dia. 2") there was no benefit in changing the design from 90° 'Tee' to 45° 'Y' joint as there was no cushion w.r.t to fluid volume once the hot fluid entered the pipe carrying cold fluid to reduce the temperature of the mixed stream near the opposite pipe wall surface. It is to be noted that fluid velocities of the hot and cold condensate streams are 0.33 m/s, 0.42 m/s respectively with flow of 2.44 m3/hr and 3.09 m3/hr respectively. Had the cold pipe size been large say 4" or above then this modification would have been successful.

The cold condensate coming from V-08 vessel at 40° C and the hot condensate coming from V-07 vessel at 160°C meet at the mixing point where differential thermal expansion is experienced due to this temperature difference of 120°C. The calculated differential expansion is of the order of 2 mm in 1metre length of the pipe. As the unit is in continuous operation, this Tee/Y mixing joint is subjected to continuous thermal cycling. Thermal stresses are generated at this mixing joint due to the hindered expansion of the pipe causing crack generation. These cracks were noticed primarily at the weld joint between the cold and hot line and in the inner surface of the pipeline downstream of the flow direction, as shown in Fig. 6.

The 'Tee' weld joint and RF pad is a stress raiser and the cracks were initiated easily at the toe of the weld causing leakage from this point. This crack had further propagated to the main pipe also due to the thermal cycling. Therefore the combined effect of thermal cycling and stress caused thermal fatigue of the mixing Tee joint leading to its failure. As per API RP 571, section 4.2.9, cracking is suspected when the temperature swing exceeds about 200°F (93° C). In this case also the temperature swings are of the order of 120°C.

4.0 CONCLUSION AND RECOMMENDATIONS

Refinery injection points are classified primarily into 3 types namely: a) Process chemical injection. eg. injection of corrosion inhibitor in column overhead (b) Wash water injection; eg. to dissolve salt deposits and wash out or dilute corrosive components and (c) Process mixing point which in our case falls under the category of process mixing point. These are also referred to as "mixing Tee" in API 570 piping inspection code. As per the survey conducted by NACE, "NACE International publication 34101" majority of problems experienced in injection points were associated with wash water injection points followed by process mixing points and the least with process chemical injection points. The commonly faced problems at injection points are localized corrosion, erosion, SCC, thermal fatigue, mechanical rupture due to pressure surge/ vibration.

The remedial measures taken to combat the failure of injection points were:(a) upgrading the material of construction, (b) increasing inspection frequency, (c) upgrading the injection type i.e providing an "quill", (d) process change, (e) piping configuration change. Of the above measures the most popular ones are (a) and (c). Both these methods have given successful results .Therefore it was decided to go for a injection quill as it was tested at other locations will great success. The design of the quill was based on good engineering practice with provision of an SS304 inner liner and retainer rings as shown in Fig. 7. The inner liner prevents direct contact of the hot fluid with the surface of the pipe carrying cold fluid thereby preventing thermal stresses. Inspection, maintenance and repair of this quill will be easy after its installation as it can be easily dismantled. This will save time during shutdown and also increase the unit run length.

Inspections of injection points shall be carried out in accordance with API-570. Although process-mixing points do not fall under the ambit of API-570, still it shall be followed for inspection purpose as it is very comprehensive. As per API-570, injection piping circuit covers 12" length or 3D (3 times the nominal pipe diameter) whichever is greater, in upstream direction from the injection point, and upto a point downstream from the injection point ending two changes in flow direction or 25 ft (7.6 m) beyond the first change of direction, whichever is less.

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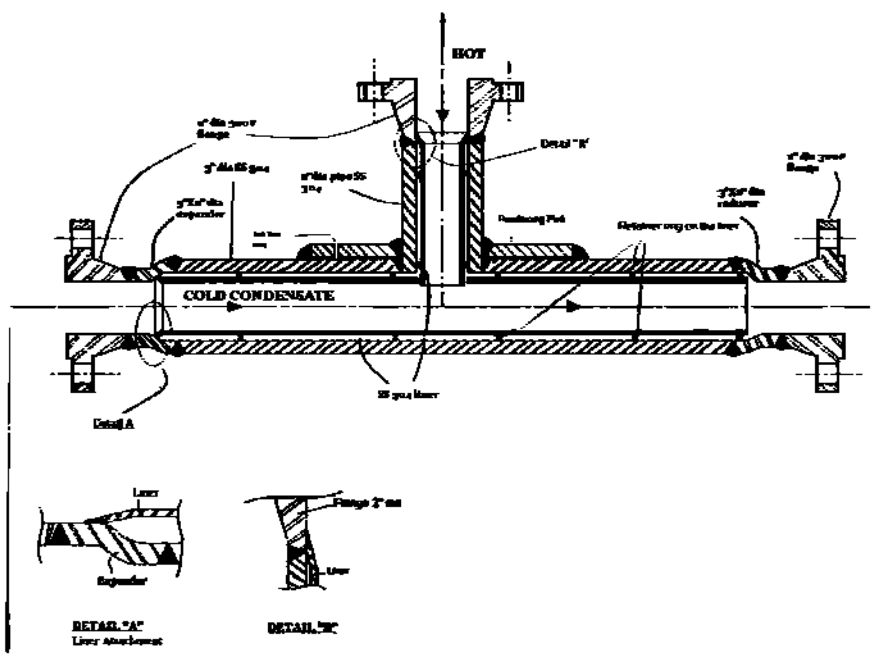

Fig. 7: Sketch of Proposed "QUILL" design for hot and cold mixing point

Notes: -

1. Both the liners may have perforations of 10 mm dia for reducing the thermal gradient on the pipe.
2. Length of the liner will be approx. 1000 mm with branch connection around 300 mm from the inlet side to maintain the same velocities. The OD at inlet will be maintained as 2" and main header dia will be increased to 3" to create annular space for minimizing thermal stresses.

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