Module 4

Design for Assembly
Lecture 8

Case Studies - IV
Instructional objectives

The objective of this lecture is to exhibit how real components are designed in industry following some of the principles that are outlines in the previous lectures.

Name of the component / part

Crevice free Tube to Tube sheet welds in Waste Heat Boiler

Function of the component / part

Heat exchangers are used to facilitate the process of heat transfer between the fluids. The shell and tube type heat exchangers are the most widely used for various industrial cooling applications such as in petrochemical and fertilizer plants. In such type of construction, the tubes, tube sheet and tube-to-tube sheet joints are based on principles of both mechanical as well as thermal design. Figure 4.8.1 schematically depicts a typical shell and tube heat exchanger. Figure 4.8.2 shows photographs of typical tube sheet, tube and tube to tube sheet joint.

![Figure 4.8.1 Schematic diagram of a typical shell and tube heat exchanger](image-url)
The tube to tube sheet joint is the most critical joint in a heat exchanger. The applicable code of construction specifies some of the standard tube to tube sheet weld joint configurations and various tests to be performed primarily from the mechanical design considerations. For example, as per ASME Sec VIII Div-2, following are the design considerations for a typical tube to tubesheet joint in case of a heat exchanger.

[a] Tubes used in the construction of heat exchangers may be considered to act as stays which support or contribute to the strength of the tube sheet

[b] Tube to tube sheet joint shall be capable of transferring the applied tube loads.

[c] The design of tube to tube sheet joint depends on type of joint, degree of examination, and shear load tests, if performed

In a tube to tube sheet joint, mechanical design is usually based on the shear strength of the joint and the tube thickness is based on the thermal design. Hence, tube to tube sheet is a perfect example of trade-off between thermal and mechanical design principles. Some of the conventional types of tube to tube sheet joints used in manufacturing of heat exchangers are shown in Figure 4.8.3.
However, over and above the requirements of standard codes, a number of additional factors need to be considered while designing tube-to-tube sheet joint for a specific application including service conditions, manufacturability, access for inspection, equipment life and ease of repair.

Service environment

Waste heat boiler is a type of heat exchanger used in fertilizer, methanol and hydrogen Plants. In reformed gas / converter gas boiler, the combinations of high pressure, high temperature and process gas composition results in higher heat fluxes in the tube inlet. This requires efficient cooling of the tubes and tube sheet, which is accomplished by keeping the tube sheet wall thickness as thin as possible. These flexible tube sheet, typically (25 to 30 mm) thick, allows good cooling by the water on the rear face and lowers the operating temperature. Boilers used in fertilizer and petrochemical process plants, which have to work at very high operating pressures require a thicker tube sheet with the thickness ranging from 300 to 500 mm e.g. synthesis loop boiler in Ammonia plant. With conventional design for the tube to tube sheet joint, high heat flux at the tube inlet causes evaporation & decomposition of water in the gap between tube & tube hole resulting in severe crevice corrosion.
Crevice Corrosion

It can be characterized as a localized attack on a metal surface at or immediately adjacent to the gap or crevice between two joining surfaces. Outside the gap or without the gap, both metals are resistant to corrosion. The damage is normally confined to one metal at localized area within or close to the joining surfaces. Crevice corrosion is initiated by a difference in concentration of some chemical constituents, usually oxygen, which set up an electrochemical concentration cell. Figure 4.8.4 shows a typical tube to tube sheet joint attacked by crevice corrosion.

![Crevice Corrosion](image)

**Figure 4.8.4** Tube to tube sheet joint attacked by crevice corrosion

On the contrary, providing a full penetration tube to tube sheet weld for this application will ascertain tube sheet integrity, eliminate the crevice on water side and ensure the stress in the weld to be same as that of on the tube sheet.

Advantages of Crevice free design

Following are considered to be advantages of crevice free joint design.

- Full Strength Joints without risk of crevice corrosion
- Volumetric Non Destructive Examination Possible
- Safest Joint Design (Can Be Used in Critical Service)

Selection of Material

Generally “metals” are chosen in the fabrication of Boilers. Tube and tube sheet material used for manufacturing of boilers should meet the following basic criteria.
- Resist high temperature H₂ attack and nitriding,
- Withstand design pressure and temperature,
- Provide sufficient ductility for forming operations,
- Provide easily weldability,
- Allow easy availability at competitive cost

Typically these tube to tube sheet joints should withstand a service condition of 400 to 450°C temperature and 5 to 300 kg/cm² (~ 0.5 to 30 MPa) working process. Further, the choice of a particular metal in hydrogen (H₂) service is based on API 941 that is also called the Nelson Curve [Figure 4.8.5]. Based on Nelson Curve and also considering the basic selection criteria mentioned above, Cr-Mo steels are the best suited for the given service conditions.
Figure 4.8.5  Nelson curve for use of material that would undergo H2 service conditions
Selection of step-wise manufacturing processes

Generally there are three different types of crevice free tube to tube sheet joints involved in manufacturing of waste heat boilers.

Single side full penetration joint (Type-I)

The through thickness narrow groove tube to tube sheet joint configuration is as shown in Figure 4.8.6.

Figure 4.8.6  Through thickness full penetration joint

This joint design calls for large-scale development of welding technology. Factors such as limited access, difficulty of gas shielding, high degree of preheat (150°C minimum) associated with creep resistant 1 ¼ Cr – ½ Mo steel and protection of weld penetration from oxidation etc. needs to be considered while selecting a suitable manufacturing (welding) procedure for producing this joint. Salient features of this type of tube to tube sheet weld is as follows

- Welding performed by manual gas tungsten arc welding process
- Full penetration joint welded in 12 to 15 layers
- Due to high thickness built-up in layers, joint safety margin is very high
- Special GTAW torches are required for welding in narrow and deep groove using long projection of tungsten electrode.
- Large diameter ceramic nozzle with suitably designed gas lens is necessary for effective argon shielding inside the groove.
- Welding filler wire shall match the composition of tube and tube sheet material
- In order to account for the distortion, welding is carried out with 2 to 3 passes at a time at various portions of the tube sheet in a staggered way
Procedures have been qualified to ASME Code and various customer specifications with dye penetrant test, radiography examination, macro & micro examination and hardness survey across the joint.

Highly skilled welders are required for producing this joint.

Lip type joint (Type-II)

Here, the weld is produced at the back face of the joint as shown in Figure 4.8.7. Difficulties addressed for welding of Type-I joint are also applicable here.

![Lip type full penetration joint](image)

**Figure 4.8.7** Lip type full penetration joint

Here, unlike the Type-I design; the welding is completed in 2 to 4 passes depending upon the tube thickness. In the current design, the minimum leak path is very critical because of less safety margin. With lesser margin of safety, the production of a sound joint with consistent quality and repeatability is of prime concern for satisfactory operation under severe working conditions thus necessitating the requirement for automation of these weld joints. Generally these welds are performed by automatic GTAW process with tube sheet in vertical position.

Full Strength Butt Joint (Type-III)

In this type of joint design, the joint is welded in single pass without addition of filler wire and hence the thickness of tube is limited to 4.5 mm. The tube inside diameter ranges from 18 to 30 mm. The typical joint configuration is shown in *Figure 4.8.8.*
Here welding is carried out by Internal Bore Welding technique from ID of the tube. The task becomes further critical due its non-accessibility since the welding has to be done at a depth of 300 – 500 mm from the Tube sheet face. The designer should have the full know-how of these requirements which would help him in selecting a suitable joint configuration for the given application.

Selection of sequential assembly processes

Many factors need to be considered while selecting the suitable assembly procedure for tube to tube sheet welding. For example, in case of Type-1 joints, channel shell is welded to the tube sheet only after completing welding of all the tube to tube sheet joints and subsequent non-destructive examinations.

In the case of Type-II joints mentioned earlier, based on the requirements for carrying out inspection of weld penetration & also to ensure proper purging of the root side, the shell course adjacent to the tube sheet is welded only after the completion of entire tube to tube sheet welding activity. Moreover, welding is done row wise as this will facilitate visual inspection from backside of the tube sheet and at the same time provide proper access for carrying out repair.

However, in the case of type-III joints, bundle layout is of fountain type. The welding sequence is selected in such a manner that there is proper access for purging, inspection, volumetric radiography & also for performing repair if any. The sequential assembly for Type-III joint with Internal Bore Welding is as shown below in Figure 4.8.9.
Possible defects and remedial measures

Table 4.8.1 lists down the possible defects that can occur during the assembly of tube to tube sheet joints and the corresponding causes and also remedial measures for the defects.
Table 4.8.1  Possible defects, associated causes and likely remedial measures during tube to tube sheet assembly

<table>
<thead>
<tr>
<th>Possible Defects</th>
<th>Cause</th>
<th>Remedial Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>In sufficient shielding &amp; purging gas, unclean base material, unclean filler, etc.</td>
<td>Sufficient flow of shielding and purging gas, proper cleaning of base metal and filler wire, etc.</td>
</tr>
<tr>
<td>Lack of fusion</td>
<td>Improper welding parameters like low current, high speed, unclean surface, etc.</td>
<td>Use of proper welding parameters, clean surface</td>
</tr>
<tr>
<td>Concave / Concave bead</td>
<td>Improper welding parameters, improper arc length, insufficient / excess flow of shielding and purging gas, etc.</td>
<td>Use of proper welding parameters, clean surface</td>
</tr>
<tr>
<td>Burn through</td>
<td>Excessive heat input</td>
<td>Reduce heat input by reducing current, increasing speed, use of heat sink, etc</td>
</tr>
<tr>
<td>Undercut</td>
<td>Improper welding parameters like high current, long arc length, high travel speed, etc</td>
<td>Use of proper welding technique and welding parameters</td>
</tr>
<tr>
<td>In complete penetration</td>
<td>Low amperage, tight root opening, high travel speed, short arc length, etc.</td>
<td>Use of proper welding technique and welding parameters</td>
</tr>
<tr>
<td>Tungsten inclusion</td>
<td>High amperage, poor quality of tungsten</td>
<td>Use of proper welding technique and welding parameters, use of good quality tungsten electrode, etc.</td>
</tr>
<tr>
<td>Crack</td>
<td>Improper preheat temperature, high restraint, unclean surface, base material impurity, etc.</td>
<td>Follow recommended preheat, ensure proper cleaning, etc.</td>
</tr>
<tr>
<td>Crater defect</td>
<td>Incorrect welding technique.</td>
<td>Use of proper welding technique</td>
</tr>
</tbody>
</table>
Testing/ Inspections methodologies

NDE/ Testing during the procedure qualification stage

Generally tube to tube sheet welds are qualified as per the code of construction. For example, following are the steps involved in qualifying a tube to tube sheet welding procedure as per ASME Sec IX.

Mockup welding

*Figure 4.8.10* depicts the details of the initial mock-up weld joints that must be produced before the final assembly is made.

![Mockup welding diagram](image)

*Figure 4.8.10* Suggested mock-up welding practices for tube to tube sheet joining

Visual Examination

The mockup weld joints shall be subjected to visual examination as below [*Figure 4.8.11*].
**Figure 4.8.11** Guidelines for visual inspection of for tube to tube sheet mockup welds

**Liquid Penetrant Examination**

Subsequently, these welds shall be subjected to Liquid Penetrant test and the acceptance criteria shall be as follows [Figure 4.8.12].

<table>
<thead>
<tr>
<th>The following indications shall be unacceptable.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relevant linear indications with length &gt; 3 times width.</td>
</tr>
</tbody>
</table>

**Figure 4.8.12** Acceptance criteria in liquid penetrant examination of tube to tube sheet mockup welds
Macro Examination

Mockup welds shall be subjected to macro-examination as per details in Figure 4.8.13.

![Guidance of macroexamination of tube to tube sheet mockup welds](image)

**Figure 4.8.13** Guidance of macroexamination of tube to tube sheet mockup welds

However, over and above the code requirements, the mockups are also subjected to various testing based on the job specification requirements like X-ray radiography and ultrasonic testing, pull out and tearing testing, crack and flaw examination, etc.

Non destructive testing in production stage

Production welding of tube to tube sheet is commenced only upon satisfactory qualification of the welding procedures and welding operators. Conventional tube to tube sheets are generally tested by dye penetrant examination after completion of welding. However, following are the non destructive testing that must be performed on the crevice free joints discussed here.
Type-I joints are subjected to visual examination, dye penetrant examination, air test and global hydro-test. The Type-II joints are subjected to visual examination on front and root side of weld, dye penetrant examination, air test, and global hydro test. The Type-III joints are also subjected to visual examination on front and root side of weld, dye penetrant examination, radiographic examination, air test, individual joint helium test, individual joint hydro test and global hydro-test.

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