Designing a high pressure feed water heater

Information from Bilfinger Power Africa

In a power generation process, the heat generated in the boiler can be used for heating purposes in other parts of the power plant in order to improve overall efficiency. A wide range of heat exchangers are used in power stations, some of which are feed water heaters, which are used to raise the temperature of the feed water before it enters the boiler economiser. This article describes the design of an efficient feed water heater.

High pressure (HP) feed water heaters are used to heat up the boiler’s feed water at high pressure and temperature before it passes back to the boiler. Fig. 1 shows an example of a shell and tube type heat exchanger which would be fitted between the feed pump and boiler. Fig. 2 shows an example of three HP heaters connected in series. To ensure the reliability of HP heaters, the quality and tightness of tube to tube plate connections are important. Depending on the design, heaters can be installed vertically, head down or head up and horizontally. This normally depends on the space available at the operational site.

Heat transfer zones
The heat transfer area in a heat exchanger can be divided into one or more of the following zones:
- Desuperheating zone
- Condensing zone
- Drain cooling zone

The different zones represent the state of the bled steam which enters the heat exchanger. In the desuperheating zone the steam is cooled from superheated state to saturated steam; in the condensing zone the steam condenses to saturated liquid and is called condensate; and in drain cooling zone the condensate is cooled further to the desired temperature.

Design input
When designing a heat exchanger the following information must be specified by the client:
- Feed water inlet temperature
- Feed water inlet pressure
- Feed water mass flow
- Required outlet feed water temperature
- Bled steam inlet temperature
- Bled steam inlet pressure
- Flash steam mass flow

In addition to the above requirements the client may also specify other design criteria such as space constraints, tube dimensions, etc.

Process calculation
Process calculation involves calculating the heat exchanger duty, operating conditions and minimum geometry requirements.
Since the pressure at desuperheating zone outlet is not known at this point the pressure can be assumed to be close to desuperheating zone inlet pressure. For pressure can be assumed to be close to desuperheating zone outlet pressure. The pressure at desuperheating zone outlet is given by following equation:

\[ P_{\text{Out}} = (P_{\text{In}} - \Delta P_{\text{Loss}}) \]  

Since the pressure at desuperheating zone outlet is not known at this point the pressure can be assumed to be close to desuperheating zone inlet pressure. For accurate calculation the \( P_{\text{out}} \) should be corrected iteratively by updating pressure drop value.

**Heat transfer requirement**

The amount of heat transfer required can be calculated using the following equation:

\[ \dot{Q}_{\text{feedwater}} = m_{\text{feedwater}} \cdot (h_{\text{out}} - h_{\text{in}}) \]  

\[ \dot{Q}_{\text{flash steam}} = m_{\text{flash steam}} \cdot (h_{g} - h_{f}) \]  

\[ \dot{Q}_{\text{bled steam}} = \dot{Q}_{\text{feedwater}} - \dot{Q}_{\text{flash steam}} \]  

where:

- \( m \) = mass flow (kg/s)
- \( h \) = enthalpy (kJ/kg)
- \( \dot{Q} \) = heat transfer (kW)

**Subscripts:**

- \( f \) = saturated gas
- \( l \) = saturated liquid

Bled steam mass flow calculation:

\[ m_{\text{bled steam}} = \frac{\dot{Q}_{\text{bled steam}}}{h_{\text{bled steam - in}} - h_{\text{bled steam - out}}} \]

**Required UA calculation**

Temperature of feed water at the inlet and the outlet of each zone can be calculated using the first and second law of thermodynamics. Once the temperature at the inlet and the outlet of the each zone is known the log mean temperature difference can be calculated.

\[ T_{\text{lm}} = \Delta T_{1} - \Delta T_{2} \]  

\[ \Delta T_{1} = \frac{\Delta T_{1}}{} \]  

\[ \Delta T_{2} = \frac{\Delta T_{2}}{} \]  

Geometry selection

The value of \( U \) (overall heat transfer coefficient) in the formula is dependent on the following factors:

- Feed water properties
- Bled steam properties
- Feed water velocities
- Bled steam velocity
- Geometry

Since the area is part of the geometry, the next step is to select the following dimensions:

- The tube's internal dimensions
- The tube's wall thickness
- Fouling factors
- The number of tubes
- Heat exchanger lengths
- Baffle lengths
- Inlet and outlet nozzle inner diameters
- Shell inner diameter

**Iterative calculation**

Once the minimum geometry is selected, calculate the pressure loss through the desuperheating zone to calculate the new saturation pressure. Repeat the calculation until the results converge. Actual area and overall heat transfer coefficient (U) for each zone can be calculated using the selected geometry and heat transfer correlations provided in many textbooks. Using the heat transfer coefficient one can calculate the required area for the heat exchanger.

**Results analysis**

At this point one has a heat exchanger process design which can meet the client's requirement but still needs to be optimised using an extensive iterative process. Once the process calculation is completed, the next step is to do a mechanical design calculation.

Materials typically used in the assembly of heat exchangers are as follows:

<table>
<thead>
<tr>
<th>Type</th>
<th>EN 10028-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3%Mo</td>
<td>16Mo3</td>
</tr>
<tr>
<td>1Cr½Mo</td>
<td>13CrMo4-4</td>
</tr>
</tbody>
</table>

**Mechanical design**

The mechanical design of a heat exchanger commences once the process design is completed. The mechanical design entails code-based calculations for the wall thicknesses of the shell, tube, tube sheet and the water box (channel).

The nozzles and their reinforcements are evaluated according to the prescribed code to ensure that there is adequate material compensated for the openings on the shell and water box. The allowable maximum loads for the nozzles are also determined. The strength of the supports is evaluated to ensure that the flooded weight of the heater and the forces and moments acting on all the nozzles can be adequately countered.

The mechanical design scope includes a finite element analysis (FEA) of the tube sheet because it is considered a thick-walled component and is subjected to numerous thermal load cases simultaneously. On the one side, half of the tube sheet experiences relatively low feedwater inlet temperatures, while the other half is at higher outlet temperature conditions. The shell side of the tube sheet is subjected to the bled steam temperatures which are higher than the water box side conditions. The FEA is done to evaluate the high secondary stresses which inherently exist inside the stress relief grooves of the tube sheet.

**Design codes**

The mechanical design is done according to the contractual requirements. The designer can design according to the following standards: EN 13445; BS 5500; ADM or ASME VIII. The American heat exchanger institute (HEI) is a valuable guideline for specifying sizes and manufacturing tolerances. Conformance to legislation also applies in the design of the heaters: SANS 347, PER and/or the OHS Act must be strictly adhered to.

**Unfired pressure vessels**

Part 3 of EN 13445 prescribes the formulae to be used for the design of pressure vessels under internal and/or external pressure. This section of the code also addresses pressure vessels of various shapes, flat walls, flanges, heat exchanger tubesheets and the design of the reinforcement of openings. Rules are also given for components subject to local loads and to actions other than pressure.

<table>
<thead>
<tr>
<th>Ap</th>
<th>Pressure loaded area</th>
<th>mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>At</td>
<td>Stress loaded cross-sectional area effective as reinforcement</td>
<td>mm²</td>
</tr>
<tr>
<td>Fs</td>
<td>Nominal design stress of shell material</td>
<td>MPa</td>
</tr>
<tr>
<td>P</td>
<td>Internal pressure of shell</td>
<td>MPa</td>
</tr>
</tbody>
</table>

**Single openings**

In Clause 9 the general equation is adapted to each of the following configurations:

Shells with openings without nozzle or reinforcing ring (with or without reinforcing pads) on cylindrical, conical and spherical shell, longitudinal and transverse cross-section.

Shells with openings without nozzle, reinforced by reinforcing rings, on all cases.

Nozzles normal to the shell, with or without reinforcing pads, on all cases.

Nozzles oblique to the shell, with or without reinforcing pads, on all cases.

<table>
<thead>
<tr>
<th>Opening configuration</th>
<th>Max. opening dimensions</th>
<th>Types of openings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single openings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiples openings</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 2: Finite element analysis.**
Basic design criteria for Part 3 are given in Clause 5 which deals with:
- Corrosion, erosion and protection
- Load cases
- Design methods
- Weld joint coefficient
- Design of welded joints

Design method
This method was developed from elements borrowed from the German code AD-Merkblatt, the British specification for unfired pressure vessels PD 5500:2000 and the French code CODAP 2000.

Wall thickness calculations
Shell under internal pressure
Section 7.4.2 of EN 13445 Part 3 - cylindrical shells states that the required wall thickness shall be calculated from one of the following two equations:

\[ e = \frac{P \cdot D_i}{2f \cdot z - P} \]  \[ e = \frac{P \cdot D_i}{2f \cdot z - P} \]  

where:
- \( e \) is the required wall thickness in mm
- \( P \) is the calculation pressure in MPa
- \( D_i \) is the internal diameter of the shell in mm

Note: The two above equations do not yield the same output, it is advisable to use the minimum required thickness \( e \) from both equations.

Openings in shells
The first proposal of CEN/TC54/WG’C’ was to use “area replacement method” that was present in ASME 8 Div. 1 and in a few European national codes (based on method of replacement of cross sectional missing area of openings with cross sectional areas of material reinforcement of shell and nozzles), but during standardisation works it was decided to adopt the “pressure-area method” because it was well known and widely used in continental Europe.

The pressure-area method is based on ensuring that the reactive force provided by the material is greater than, or equal to, the load from the pressure. The former is the sum of the product of the average membrane stress in each component and its stress loaded cross-sectional area.

![Fig. 3: Temperature change across the heat exchanger.](image-url)
The latter is the sum of the product of the pressure and the pressure loaded cross-sectional areas. If the reinforcement is insufficient, it shall be increased and the calculation repeated.

A shell containing an opening shall be adequately reinforced in the area adjacent to the opening. This is to compensate for the reduction of the pressure bearing section. The reinforcement shall be obtained by one of the following methods:

- Increasing the wall thickness of the shell above that required for an un-pierced shell,
- Using a reinforcing plate,
- Using a reinforcing ring,
- Increasing the wall thickness of the nozzle above that required for the membrane pressure stress,
- Using a combination of the above.

The general equation for the reinforcement of an isolated opening is given by: (see Eqn. 9 below).

Finite element analysis

Finite element analysis is used in the design of heat exchangers to model the complex behaviour of the tube sheet and to quantify the resulting secondary stresses inside the relief grooves. The temperature distribution over the tube sheet surfaces is modelled according to the operating conditions of the steam and feedwater. The thermal transfer coefficients on the surfaces of the tube sheet are determined and used in establishing the mechanical loads onto the tube sheet.

Explosive welding process

Explosive welding is a solid state welding process, which uses a controlled explosive detonation to force two metals together at high pressure. The resultant composite system is joined with a durable, metallurgical bond.

When an explosive is detonated on the surface of a metal, a high pressure pulse is generated. This pulse propels the metal at a very high speed. If this piece of metal collides at an angle with another piece of metal, welding occurs. For welding to occur, a jetting action is required at the collision interface. This jet is the product of the surfaces of the two pieces of metals colliding. This cleans the metals and allows pure metallic surfaces to join under extremely high pressure. The metals do not mix, they are atomically bonded. Therefore, any metal may be welded to any metal, i.e. copper to steel; titanium to stainless, and so on.

The time duration involved in the process is short, resulting in a reaction zone between the constituent metals which is microscopic. During the explosive welding process, several atomic layers on the surface of each metal become plasma. The plasma is forced by the collision angle to jet ahead of the collision front, effectively scrubbing both surfaces and leaving virgin metal.

The bond line is an abrupt transition from the clad metal to the base metal with virtually no degradation of their initial physical or mechanical properties. Any usual joining method which uses heat may cause brittle inter-metallic compounds to form.

Parameters to be controlled when performing explosive welding process

- Detonation velocity
- Explosive load
- Interface spacing

In the reaction zone, the two constituent metals can be considered as viscous fluids just as in describing laminar or turbulent flow. The wave pattern formed at the bond line (see Figs. 6 and 7) is most often described as resulting from a fluid-flow collision. A Reynolds number can be determined for the system. It is important to know the metallurgy involved in a particular system when selecting bonding parameters. In very turbulent wave patterns, localised melt pockets can occur at the crests of the waves. These melt pockets can contain a variety of binary alloys, rapidly-solidified microstructures and inter-metallic compounds. Some systems which form a very stable inter-metallic compound may form a continuous layer of that compound at high bonding pressures. The formed bond with a continuous inter-metallic layer usually shows very high tensile strength, but low ductility and impact resistance. It will also react poorly to the thermal cycling.

Uses of explosive welding

- It is used in the joining of pipes and tubes
- Tube plugs are normally manufactured with a nickel shell
- They are mainly used in heat exchanger tube sheets and pressure vessels
- Used for remote joining in hazardous environments
- Attaching cooling fins

\[
KAf_2 + Af_2(f_{ob} - 0.5P) + Af_2(f_{ob} - 0.5P) + Af_2(f_{ob} - 0.5P) \geq P(Af_2a + Ap_2 + 0.5Ap_2) \tag{9}
\]

Eqn. 9.

- Advantages of explosive welding
  - It can bond many dissimilar, normally unweldable metals. The high integrity of the bond allows design engineers to utilise the specific desirable properties of metals more efficiently. (Cannot only be used in weld combinations of most commonly used materials in heat exchanger manufacture, but also unusual combinations which cannot be welded by other means, such as admiralty brass tubes to carbon steel tube plate).
  - It needs minimum jigs
  - It is a simple and quick process
  - Can be ultrasonically tested
  - Extremely large surfaces can be bonded
  - A wide range of thickness of various materials can be explosively clad together
  - It does not have an effect on parent properties
  - A small quantity of explosive is used
  - Leak tightness can be confirmed on-site using hydraulic or pneumatic tests. During testing, plugs have been subjected to an external pressure of 69 MPa and an internal pressure of 3241 MPa.
  - No pre or post weld heat treatment is required.
  - Welds are not affected by thermal cycling therefore the process is ideally suited for heat exchangers such as HP feed water heaters.
  - Welds have been subjected to severe thermal cycling and the vessel pressure tested to 69 MPa without leaking.
  - During thermal cyclic testing, plugs/tube sheets have been heated to 700°C and then plunged into cold
Despite the extreme thermal shock applied to the joints, they remained tight, even after an external hydraulic pressure test of 69 MPa.

The weld process, which is a true metallurgical bond, is far superior to conventional welding. Weld penetration of a typical front face tube to tube sheet weld is in the order of 1 – 1.5 mm whereas with explosive welding typical weld lengths in the order of 7 – 10 mm can be achieved.

The weld is stronger than the weaker of the two materials being joined.

The welding process automatically creates a very tight expansion of the tube in the parallel section of the hole immediately behind the weld area. Welds have been removed by machining and the expansion itself has been shown to be leak tight to 14 MPa.

Explosive welded plugs in a feed water heater

Mechanically fitted or fusion welded plugs have been used in the past for effecting repairs to leaking heat exchanger tubes and/or joints. Welding a plug into a feed water heater on-site is an extremely difficult job. The working conditions are normally very poor, and in plant breakdown situation, conditions can rarely be improved sufficiently to allow the weld preparation and the weld process itself to be carried out with the degree of precision required for the task. Also in recent years the use of high pressure/temperature exchangers has revealed shortcomings in those traditional methods of repair.

Introducing explosively welded plugs (Fig.4.) provides an economical and highly reliable method of overcoming these problems. These plugs have proved 100% effective from the company that has inserted them.

From Fig. 5, the tube bore or tube plate hole requires little preparation. This is to remove surface oxides and scale from the weld area, no machining of the hole is required. The plug containing an explosive charge which is inserted into the prepared tube/ tube plate hole, and the charge initiated to produce an explosive weld between the plug and the tube or tube plate.

Conclusion

The design methodology proposed here will result in an efficient water heating solution. Feeding pre-heated water into a boiler reduces the temperature strains associated with cold water feed-in, and reduces the time required to convert the water into steam, with resultant fuel savings. Another advantage of heating feed water is that the ingredients which form scale are removed prior to the water entering the boiler, improving boiler efficiency and capacity.

Contact Susanne Hattingh, Bilfinger Power Africa, Tel 011 806-3012, susanne.hattingh@powerafrica.bilfinger.com.