Design and technology parameters influence on durability for heat exchangers tube to tubesheet joints

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Abstract. The main failures of heat exchangers are: corrosion of tubes and jacket, tubes blockage and failures of tube to tubesheet joints also by corrosion. The most critical zone is tube to tubesheet joints. Depending on types of tube to tubesheet joints, in order to better respect conditions of tension and compression, this paper analyses the tubesheet holes shapes, smooth and with a grove, on corrosion behavior. In the case of welding tubes with tubesheet, welding parameters modify corrosion behavior. Were realized welded joints by three welding regimes and tested at corrosion in two media, tap water and industrial water. Were tested also samples made of smooth tubes, finned tubes and tubes coated with a passive product as applied by a heat exchanger manufacturer. For all samples, the roughness parameters were measured, before and after the corrosion tests. The obtained corrosion rates show that stress values and their distribution along the joint modify the corrosion behavior. The optimum welding parameters were established in order to increase the joint durability. The paper has shown that passive product used is not proper chosen and the technology of obtaining rolled thread pipes diminishes tubes’ durability by increasing the corrosion rate.

1. Introduction
A heat exchanger is an equipment built for efficient heat transfer from one fluid to another, where the fluids are separated by a solid wall so that they never mix, or are directly contacted. They are widely used in chemical processing, heating, refrigeration, air conditioning, power production etc. Typical functions of heat exchangers are heating or cooling. Shell and tube heat exchangers are most commonly used in the process refinery industries due to a large ratio of heat transfer area to volume and weight. Shell and tube heat exchangers consists of a shell surrounding a bundle of tubes. Two fluids, of different inlet temperatures, flow through the exchanger. One fluid flows through the tubes and the other flows through the shell. Heat is transferred from one fluid to the other. The general coding guidelines [1] define heat exchangers failures as follows:

• "State of other components". The cause of the state of the component under consideration is due to state of another component. Examples are loss of power and loss of heating/cooling capacity.

• “Design, manufacture or construction inadequacy”. This category contains actions and decisions taken during design, manufacture, or installation of components, both before and after the equipment is operational. Included in the design process are the equipment and system specification, material specification, and initial construction that would not be considered a maintenance function. This category also includes design modifications.
• “Abnormal environmental stress”. Represents causes related to a harsh environment that is not within component design specifications. Specific mechanisms include chemical reactions, electromagnetic interference, fire/smoke, impact loads, moisture (sprays, floods, etc.) radiation, abnormally high or low temperature, vibration load, and severe natural events.

• “Human actions”. Represents causes related to errors of omission or commission on the part of plant staff or contractor staff. An example is a failure to follow the correct procedure. This category includes accidental actions, and failure to follow procedures for construction, modification, operation, maintenance, calibration, and testing. This category also includes deficient training of operators.

• “Maintenance”. All maintenance not captured by H - human actions or P - procedure inadequacy.

• “Internal to component, piece part”. Deals with malfunctioning of parts internal to the component. Internal causes result from phenomena such as normal wear or other intrinsic failure mechanisms. It includes the influence of the environment of the component. Specific mechanisms include erosion/corrosion, internal contamination, fatigue, and wear out/end of life.

• “Procedure inadequacy”. Refers to ambiguity, incompleteness, or error in procedures for operation and maintenance of equipment. This includes inadequacy in construction, modification, administrative, operational, maintenance, test and calibration procedures. This can also include the administrative control of procedures, such as change control.

• “Other”. The cause of events is known, but does not fit in one of the other categories.

• “Unknown”. This cause category is used when the cause of the component state cannot be identified.

The dominant failure causes based on ICDE codes [1] is “Abnormal environmental stress” accounting for 28% of the events, followed by “Design, manufacture or construction inadequacy” and “Internal to component, piece part” accounting for 26% of the events each. In the majority of the events, failures occur at equipment’s working in aggressive environment and were affected heat exchanger internals as tubes, plates, chambers in multiple trains and components [2]. Observed failures have also lead to leaks and impeded flow due to corrosions (corrosion, erosion) and dirt accumulation (pitting debris, fouling) [2]. There are also direct human/operator related faults causing dependencies of heat exchanger trains, e.g. by faulty alignment of valve configuration and wrong maintenance procedures and/or practices [2].

In conclusion the main failures at heat exchangers are caused by corrosion. Not only working parameters, harsh media and materials used influence corrosion rate but also the design, the manufacture parameters and the construction influence corrosion behavior and durability of heat exchangers.

To increase the heat exchange efficiency the tubes surface could be finned or made a thread by rolling [3], but internal stresses due to plastic deformation modify electrochemical potential and material became anodic [4].

The tubes are held in place by being inserted into holes in the tubesheet and there either expanded into grooves cut into the holes or welded to the tube sheet. The most critical zone to corrosion at heat exchangers is tube to tubesheet joints.

Depending of types of tube to tubesheet joints, in order to better respect conditions of tension and compression, this paper analyses the tubesheet holes shapes, smooth and with a grove [5], above corrosion behavior. In case of welding tubes with tubesheet, welding parameters modify corrosion behavior.

There were also tested samples made of smooth tubes, finned tubes and tubes coated with a passive product as applied by a heat exchanger manufacturer. At all samples were measured the roughness parameters before and after corrosion tests.

The obtained corrosion rates show that the stress value and its distribution along the joint modify corrosion behavior.

Were established the optimum welding parameters in order to increase joints durability. It was shown that passive product used is not proper chosen and the technology of obtaining rolled thread pipes diminishes tubes durability by increasing the corrosion rate.
2. Heat exchanger, construction, materials and working conditions

The analysed heat exchanger is type NEN as classified by Tubular Exchanger Manufacturers Association (TEMA) [6] and it is presented in figure 1. The main working parameters are shown in table 1.

![Figure 1. Heat exchanger batery type NEN.](a) Scheme of heat exchanger; b) Photo of heat exchanger.

For the analyzed heat exchanger, steam is circulating through the jacket and through the tubes is circulating industrial water which will be heated.

| Parameter                          | Shell chamber | Tubes chamber |
|------------------------------------|---------------|---------------|
| Capacity (m$^3$)                   | 1.31          | 0.55          |
| Number of crossings                | 1             | 1             |
| Fluid                              | Gas           | Industrial water |
| Maximum working pressure (MPa)     | 3.79          | 4.92          |
| IN/OUT working temperature (°C)    | 199 / 185     | 21 / 49.5     |
| Material                           | ASTM 516 Gr.70 / EN 10028 | ASTM 344 Gr.6 / EN 10028 |
|                                    | P355 GH       | P265 GH       |

To design the heat exchanger, manufacturer used PV Elite software programme. PV Elite is used also for analysing heat exchangers and pressure vessels and it is compliant with ASME Section VIII Divisions 1 & 2, PD 5500, EN 13445 and API 579.

3. Experimental tests

3.1. Tests on extruded tube to tubesheets joints

The joints between tubes and tubesheets must resist to axial stress which appear in tubes. This condition is fulfilled when tubes and tubesheets were made of steel and when the hoop stress in tubesheet is higher than in tubes [5, 7]. In order to evaluate residual stresses at tube to tubesheets expanded joints above tubes corrosion behavior were prepared samples as presented in figure 2 for tubesheets and in figure 3 for tubes. Samples were prepared at real joints dimensions and tubesheet sample of material P 355 GH and tubes of material P 265 GH EN 10028.
Samples were expanded to obtain joints between tubes and tubesheets. Parallelepiped shape samples for corrosion tests were extracted and machined from tubes, without affecting the material structure, as follows:

- “A” type samples extracted from tubes not used for expanded joints;
- “B” type samples extracted from tubes from expanded joint with smooth tubesheet boring surface;
- “C” type samples extracted from tubes from expanded joint with a rectangular groove on tubesheet boring surface;
- “D” type samples extracted from tubes from expanded joint with elliptic grooves on tubesheet boring surface.

Working medium were industrial water with $pH = 7.18$, conductivity $= 1524 \mu S/cm$, total solid deposition $TDS = 42 \text{ mg/l}$ and medium temperatures were 20, 40 and 60 $^\circ\text{C}$ [5].

For immersion corrosion tests the corrosion rate was obtained with the relation [4]:

$$v_{cor} = 8.76 \cdot \frac{m_f - m_i}{A \cdot \tau \cdot \gamma}, \text{ mm·year}^{-1} \quad (1)$$

where $m_f$ is sample final mass, g;
$m_i$ - initial sample mass, g;
$A$ - sample area, m$^2$;
$\tau$ - time, hours;
$\gamma$ - specific weight, g·cm$^{-3}$.

In figure 4 it is shown the obtained corrosion rate vs. time at testing temperatures in industrial water.
Figure 4. Corrosion rate results for extruded tubes samples. 
(a) Corrosion rate vs. time at 20°C in industrial water;  
(b) Corrosion rate vs. time at 40°C and 60°C for samples types “D”.  

Similar results as presented in figure 4b for corrosion rate were obtained for samples extracted from extruded tubes types “A”, “B” and “C”.  

3.2. Corrosion tests on tubes samples with different surface geometry  
In order to evaluate corrosion behavior of tubes with different geometry were prepared tubes samples as follows:  
- “E” type samples with finned surfaces obtained by rolling;  
- “F” type samples with smooth surface tubes with roughness parameter $R_a = 1.35 \mu m$ as obtained by tubes manufacturer treated or not treated (passivated) with the corrosion inhibitor product type VmCI-307™;  
- “G” type samples with smooth tubes with $R_a = 1.55 \mu m$ obtained by turning treated or not treated with the corrosion inhibitor product type VmCI-307™.  

Figure 5 presents the finned tubes samples and figure 6 the smooth tubes samples.  

Figure 5. Finned tube sample.  
Figure 6. Smooth tube sample.  

Testing media were tap water and industrial water with characteristics presented above in section 3.1. Before immersion samples were measured, weighed with an analytic balance. In samples tubes holes, rubber plugs were fixed to avoid corrosion inside the tubes. The immersion time was 338 hours at ambient temperature of 20°C. Table 2 presents the results of corrosion rate.
Table 2. Corrosion rate results for different tubes surfaces.

| Sample type | Medium                  | Temperature, (°C) | Time, (hours) | Corrosion rate, $v_{cor}$ (mm·year$^{-1}$) |
|-------------|-------------------------|-------------------|---------------|--------------------------------------------|
| “E”         | Tap water               |                   |               | 0.097                                      |
|             | Industrial water        |                   |               | 0.127                                      |
| “F”         | Tap water               |                   |               | 0.051                                      |
|             | Industrial water        |                   |               | 0.065                                      |
| “F” passivated with VmCI-307™ | Tap water               | 20               | 338           | 0.062                                      |
|             | Industrial water        |                   |               | 0.069                                      |
| “G”         | Tap water               |                   |               | 0.056                                      |
|             | Industrial water        |                   |               | 0.066                                      |
| “G” passivated with VmCI-307™ | Tap water               |                   |               | 0.067                                      |
|             | Industrial water        |                   |               | 0.071                                      |

3.3. Tests on samples welded with different welding parameters

At heat exchanger critical zones are tube to tubesheets joints as presented above. Many heat exchangers manufactures still realize welded joints between tubes and tubesheets. At heat exchanger battery type NEN presented in figure 1 were established GTAW welding parameters. In order to evaluate the influence of welding parameters on corrosion behavior, tree types of samples were prepared and were immersed for 360 hours in tap water and in industrial water, respectively, at ambient temperature of 20°C:
- “H1” type samples welded with a 12% reduction of recommended welding parameters, for immersion in tap water;
- “H2” type samples welded with a 12% reduction of recommended welding parameters, for immersion in industrial water;
- “L1” type samples welded with recommended welding parameters, for immersion in tap water;
- “L2” type samples welded with recommended welding parameters, for immersion in industrial water;
- “M1” type samples welded with a rise with 12% of recommended welding parameters, for immersion in tap water;
- “M2” type samples welded with a rise with 12% of recommended welding parameters, for immersion in industrial water;

These samples were prepared by GTAW welding of real tubes to real plate as shown in figure 7.

Figure 7. Samples welded joints.

After welding samples were extracted by milling from plate, and microgeometry parameters were measured for tubes inside surface and plate surface in HAZ (heat affected zone) with Surtronic 3+ device. In figure 8, the measurement images are presented. Microgeometry profile was measured before and after 360 hours of immersing in testing media.
Table 3 shows the sample welding parameters. Plate was of material P 355 GH and tubes of material P 265 GH EN 10028. Was used gas tungsten arc welding (GTAW) and wire with Ø1.6 mm type BÖHLER EML 5 that can be used in sour gas applications (HIC-Test acc. NACE TM-02-84).

| Samples type   | Welding current (A) | Voltage (V) | Welding time (sec.) | Linear welding energy (kJ·cm⁻¹) | Welding speed (cm·min⁻¹) |
|----------------|---------------------|-------------|---------------------|---------------------------------|--------------------------|
| H1 and H2      | 90                  | 8           | 118                 | 7.3                             | 5.9                      |
| L1 and L2      | 115                 | 12          | 70                  | 12.7                            | 6.5                      |
| M1 and M2      | 140                 | 14          | 50                  | 14.7                            | 8                        |

Table 4 presents the times of first observation of iron oxides on samples surfaces. Samples types “H1”, “L1” and “M1” were immersed in tap water and samples types “H2”, “L2” and “M2” in industrial water with the same composition as presented above in section 3.1.

| Samples type   | Time of iron oxides first observation, (hours) |
|----------------|------------------------------------------------|
| H1             | 31                                              |
| L1             | 33                                              |
| M1             | 35                                              |
| H2             | 21                                              |
| L2             | 23                                              |
| M2             | 23                                              |

In table 5 are presented the roughness values pointing out the sample surface modifications.

| Samples type   | Roughness parameters (µm) | Roughness parameters (µm) |
|----------------|---------------------------|---------------------------|
|                | $R_a$                      | $R_t$                      | $R_z$                      |
| H1 plate       | +1.203                    | +8.94                     | +8.42                     |
| H1 tube        | -0.920                    | -19.70                    | -10.10                    |
| L1 plate       | +0.673                    | +9.39                     | +6.87                     |
| L1 tube        | +2.470                    | +4.80                     | +5.90                     |
| M1 plate       | +0.897                    | +7.82                     | +4.60                     |
| M1 tube        | -3.380                    | -17.80                    | -14.00                    |
| H2 plate       | +1.875                    | +15.32                    | +10.80                    |
| H2 tube        | -2.610                    | -32.40                    | -20.10                    |
| L2 plate       | +1.671                    | +11.90                    | +10.96                    |
| L2 tube        | +3.120                    | +0.80                     | +8.70                     |
| M2 plate       | +1.584                    | +9.85                     | +9.37                     |
| M2 tube        | +1.050                    | +4.00                     | +4.10                     |

*a* Sign “+” signifies roughness increase and “-” signifies roughness diminish.

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Figure 8. Microgeometry measurements. (a) Measurement inside the tubes; (b) Measurement on plate surface.
In order to better analyze the welding parameters on HAZ were made Vickers with low load hardness measurements HV3 at samples types “H”, “L” and “M”. In figure 9 are shown the hardness vs. distance values for tested samples. Hardness measurements starts at 0.3 mm from inside surfaces of tubes welded in plate and continue on a distance of 10 mm on the plate surface.

![Figure 9. Hardness values for tested samples.](image)

As it could be observed from figure 9, because hardness values were smaller than 230 HV3, similar to base material, was not necessary to measure hardness at greater distances on plate surfaces.

4. Conclusions

The obtained experimental tests results show that at expanded tube to tubesheets joints, the residual stress influences the corrosion behavior (see figure 4a). The plate boring surface with a rectangular groove shape and with smooth shape also conduct to smaller corrosion rates than those bringing surface with elliptic groves (see figure 4a).

Durability of heat exchangers depends not only on materials’ corrosion resistance, but also on the joint stability under axial stresses due to tension or compression. Hence, smooth joint surfaces are not recommended because these joints do not resist to axial stresses which appear in tubes. Tubesheets with elliptic groves or rectangular groves on holes’ surfaces are better.

Temperature also modifies the corrosion rates. The temperature influence in increasing corrosion rate is smaller at tubesheets with elliptic groves than those with rectangular groves or smooth holed surfaces.

Tubes shape also modify corrosion rate. Finned tubes obtained by rolling conduct at higher corrosion rates than smooth tubes (see table 2). All cutting operations, including turning (at tubes) or boring (at tubesheet), even are made with cooling fluids and at low cutting parameters modify electrochemical potential at the material surface and increase the corrosion rate.

Not all corrosion inhibitor products have a benefic effect in reducing corrosion rate and increasing equipment durability. Even at tested materials spread used for tubes and tubesheets construction, the corrosion inhibitor product type VmCl-307™ also spread used, conduct to a higher corrosion rate than without this product, as could be observed from table 2.

For the welded joints, welding parameters influence the corrosion rate (see table 4 and table 5), due to the microstructure transformations. The heat affected zones, where the stresses are maximum, are also critical zones for corrosion. For tested welded materials, the parameters with 12% higher values than the recommended values, conduct to better results. The times of oxide observations were longer,
the surfaces of tubes and plates roughness modifications were smaller and the hardness curve presented in figure 9 shows that HAZ and the hardness gradient are smaller.

References

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