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CFD and FEA Boiler Collector Analysis

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This article presents a troubleshooting analysis of a steam boiler which serves for steam overheating. Operating of this boiler is accompanied by unexpected difficulties – repetitive crack occurring on a boilers collector (Figure 1). Therefore, the substantial part of this paper is focused on identifying of the main reason of damaging. The first step in damage identification was static, respective quasi-static FEM (finite element method) analyses. These analyses did not confirm the cause of damaging. Therefore, it was approached to analytical calculations (thermal – hydraulic and vibration calculations) which were used for additional boundary conditions estimation. The vibration analytical analyses predicted vortex excitation. The occurrence of vortex excitation behind the tube (Figure 6) was subsequently confirmed by CFD (computational fluid dynamics) and FSI (fluid structure interaction) analyses. These analyses revealed the cause of tube bundle damaging, which was fluid induced vibration. Significant part of this article is devoted to discussion about used computational models, boundary conditions and results of analyses. The last part of this article is targeted at proposing corrective action.

1. Introduction

The analysed collector (Figure 3) is a part of a steam boiler where flue gas flows on the temperature of 486 °C. The main role of the boiler is to overheat steam in a U - tube bundle to the operating temperature of 375 °C. In the past, inspection of the device was performed. The measurements indicated the most critical location with respect to operational stability. It was the collector situated at the entrance of flue gas in the second pass of the boiler. The surface cracks were detected on outer surface, particularly between tubes nozzles (Figure 1, Figure 3). In 2005, this part had to be replaced due to the excessive crack development. It is obvious that this collector is the weakest pressurized part of the boiler. The necessity of replacement is periodical. It occurs within four to five years of operation and has direct impact on uniformity of operation, financial costs and ecological burdens. The occupancy of the boiler do not allow shutdown of the unit, and in terms of safety and economy, it was not necessary to do so (not critical length of the crack). Due to these circumstances, it was not possible to take samples from the collector and do closer examination of the crack and other factors which can influence initiation and distribution of damages. When shutdown, these factors, such as fouling, deformation of membrane walls, tubes baffles and composition of fuel, will be carefully examined. Meanwhile, there were prepared mathematical models which serve to preliminary analyses of the presented issue. The main task of this article is to create numerical models which examine possible damaging factors and their impact to the device. The analyses were sequentially performed from the easiest, with capability to provide necessary answers, to more complicated and complex analyses. The first analysis was focused on static (quasi - static) check. Pressure, temperature and their combination (with global and local boundary conditions) were used as the boundary conditions. These analyses, performed by FEA (finite element analysis), did not resulted in identifying damage mechanism; the obtained results did not shown significant stress concentration which could be potentially dangerous to the collector. Thus, it was approached to the analytical analyses (thermal – hydraulic and vibration). The aim of these analyses was to obtain a more accurate boundary condition which could be used for more advance analyses. Thermal-hydraulic check calculation provided heat transfer coefficients and medium velocities for both sides of the tube bundle. This thermal-hydraulic

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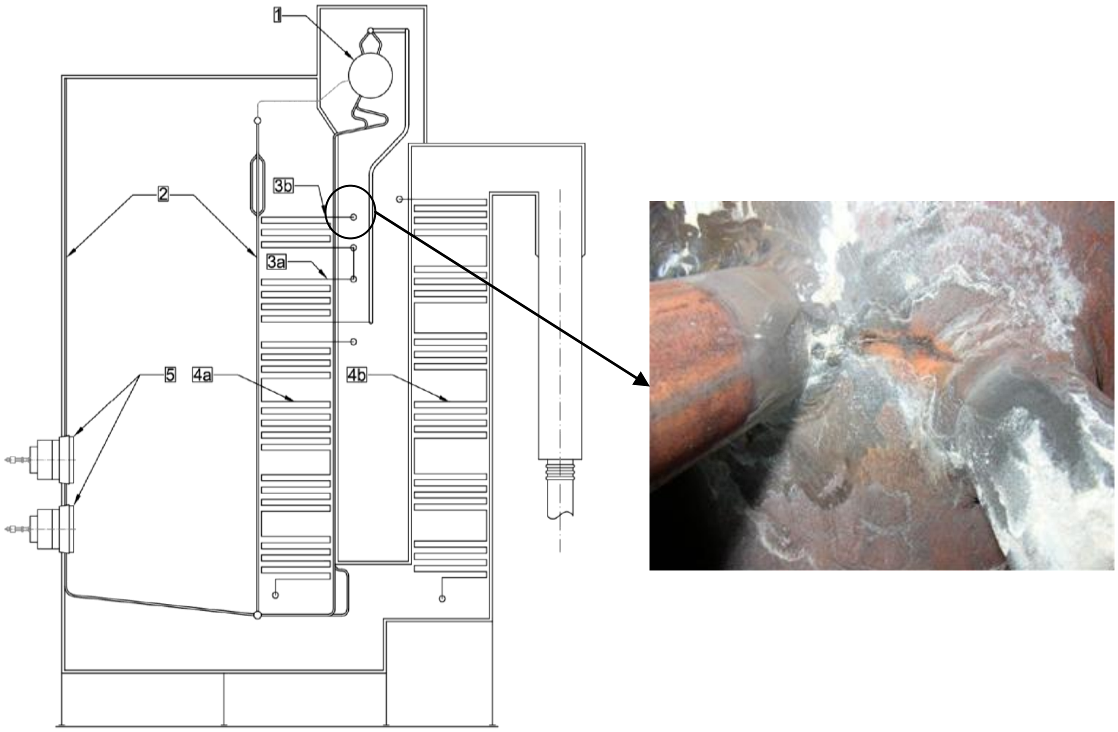

Figure 1: Description of the boiler

calculation took into account heat duty of the tube bundle and influence of fouling to heat duty. The subsequent vibration analysis confirmed the presence of fluid-induced vibration. These vibrations are induced by vortex excitations which are formed behind the tubes. To confirm analytical results, CFD and FSI analyses were performed and proved their accuracy.

2. Boiler description

The steam boiler (Figure 1) is a three-pass boiler with natural draught. It was designed to burn tar mixtures, natural gas and heavy fuel oil. Its operation conditions are shown in Table 1. Walls of a burning chamber and a second-pass are formed by en evaporator (Figure 1). Burners are located on the evaporator wall (Figure 1). A rear membrane wall of the second draught is formed by water tubes. Heating surfaces of a superheater (Figure 1) and parts of the heater are located horizontally at the second draught. All tubes are hanged on supports (Figure 2). The second part of the heater is located at the third draught (Figure 1) also in a horizontal position and positioned on the supports. The regulation of the superheated steam temperature is realized by injection of water into the steam in injection regulators. All heating surfaces are arranged horizontally, which allows the easy reduction of its water content.

The steam boiler has been in operation since 6/11/95 and it has 40 % of expected life remaining. During the time, there has not been any other damage, except the mentioned collector replacement. In order to provide stable operation in the future, it was necessary to assess its condition and to propose a repair plan which will be implemented during next shutdown.

The critical area of the collector with the crack between nozzles can be seen on Figure 1 and Figure 3.

Table 1: Operating parameters of the boiler

	Unit	Value		Unit	Value
Steam performance	t/h	120	Evaporator temperature	°C	310
Steam pressure	MPa	3.82	Superheater pressure	MPa	3.82
Steam temperature	°C	375	Superheater temperature	°C	375
Drum pressure	MPa	4.25	Heater pressure	MPa	4.25
Drum temperature	°C	254	Heater temperature	°C	250

Evaporator pressure	MPa	4.25	Flue gas temperature	°C	490

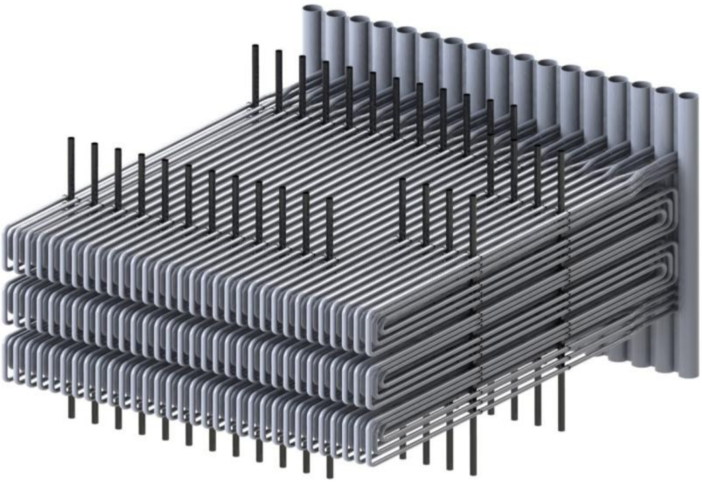

Figure 2: U-tube bundle supports

Damage to the collector occurs always at hoop direction of the shell. The cracks are situated between two nozzles of neighbouring tubes (Figure 3), mainly in the middle part of the collector. The tubes pass through the membrane wall to the combustion chamber of the boiler where heat transfer occurs (Figure 2). The collector and the part of the connected tubes are not located in the area of flue gas. The bundle of U-tubes with several rows was designed to provide sufficient space for temperature dilatations.

3. Analysis

3.1 FEM analyses

First of all, a series of numerical analysis was performed by using of Ansys inc software. The static structural analysis with linear elastic material model, where the possibility of local high stresses at the area of connection of collector and tubes was performed. This analysis did not confirm the appearance of stresses during operation, which could result in the initiation of the crack. In addition, the analysis was extended by the temperature boundary condition. At this point, a detailed submodel for more accurate results was created. However, this analysis also did not confirm the crack appearance. The next static structural analysis included non-homogenous temperature field. Overheating of first tubes of the tube bundle was considered. This condition was chosen because of the 90° arrangement of the tubes and due to the lower heat transfer at lower tubes caused by flow velocity. Not even this analysis did confirm expected mechanism of failure.

3.2 Thermal-hydraulic analyses

To analytical thermal-hydraulic analyses was approached in order to receive boundary conditions such as heat transfer coefficients (both in shell side and tube side), flue gas velocity in shell side and fouling resistance in the shell side and tube side. These analyses were performed according to Kern's method for shell and tube heat exchanger. Typical values defining the geometry of the shell and tube heat exchanger were replaced by geometrical values of the boiler. Certain deviations are possible due to uncertainty of the flue gas composition. Thus, thermophysical values such as specific heat, thermal conductivity, dynamic viscosity and density considered as constant (independent on the flue gas temperature change). The value of heat transfer coefficient for flue gas in the shell side is 1,124.06 W/(m^2.K) and for steam in the tube side it is 35.86 W/(m^2.K). The flue gas velocity in the shell side is 1.25 m/s. The fouling resistance was determined according to (Hewitt, 1998) as 0.0008 (m^2.K)/W for flue gas and 0.0001 (m^2.K)/W for steam.

3.3 Fluid induced vibration analysis

The next analysis is focused on vibrations induced by fluid flow. Vibrations of tubes should be a significant factor of damaging. The influence of vibrations can be even bigger when supports of the tube bundle are not designed properly.

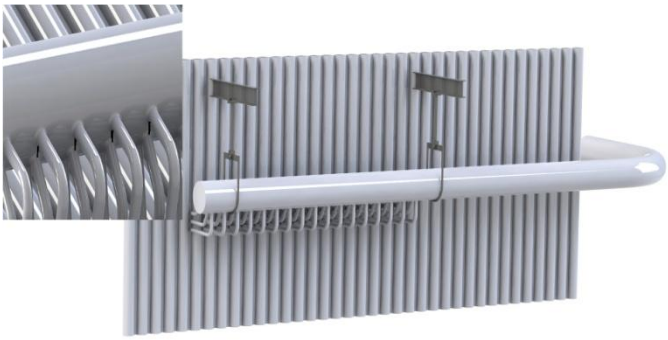

Figure 3: Membrane wall, tube and collector connection

Firstly, analytical calculations of vibration according to (TEMA, 2007) were performed. The calculations confirmed the possibility of vibration induced by vortex excitation and acoustic emission from flue gas flow. The natural frequency of selected U-tubes parts is almost identical with the frequency of vortex excitation. The interaction of acoustic emission with vortex excitation should cause an increase of oscillation amplitude. Maximum values of the amplitude from vortex excitation A_w and turbulent excitation A_t are shown in Table 2. This table is related to Figure 2 and Figure 4. Figure 4 shows tube connection with fixed supports at the ends and simple supports between parts I to XV. Each part IV, VI, VIII, X, XII of the tube then represents one U – tube part. Function on Figure 4 shows dependence of mode shape on tube length. Simple supports located between section I, II and XIV, XV also represents tube connection with membrane wall as shown on Figure 2.

Table 2 compares individual maximal amplitudes of tubes, which serves for outlining of allowable vibration limit exceeding. All values of amplitude A_t are in comparison with (VDI-heat atlas, 2010) allowable value (0.76 mm) exceeded. The occurrence of the acoustic vibration is assessed by means of damping parameter G. The limiting value for the creation of acoustic vibrations is according to (VDI-heat atlas, 2010) G > 2,700. In this particular case G = 273,572.4. Flow-induced vibration analyses confirmed the occurrence of amplitudes higher then allowed. It will result in tube vibrations in the tube bundle in the shape of waves. These waves could be added or subtracted in the connection of tubes, as shown on Figure 2. Important assumption of the waves transfer through the tube and membrane wall connection is insufficient rigidity of this connection. Above described mechanism will lead to damage accumulation and to the crack occurrence on the collector eventually. Assumptions were made for the analytical analysis of vibration series. In particular:

- Start-up of the steam boiler is expected to be slowly gradual.
- Continual operation is supposed to be operating with a constant composition of fuel.

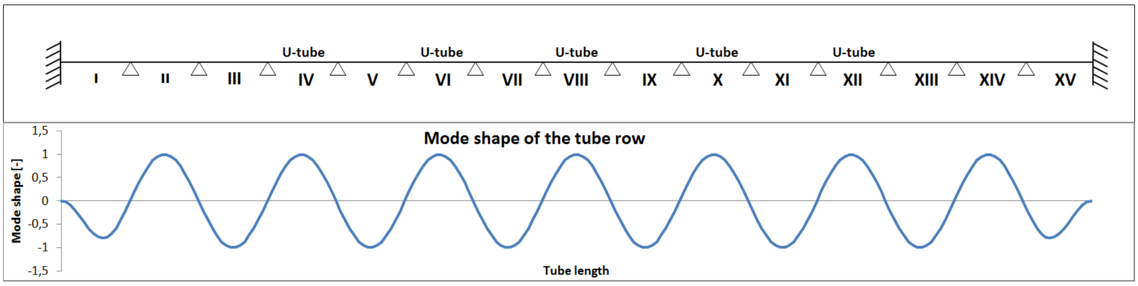

Figure 4: Supports of tube bundle

Table 2: Maximum values of amplitude for parts of the tube bundle

	A_t [mm]	A_w [mm]		A_t [mm]	A_w [mm]
First tube row, last four columns	7.012	0.07	other columns	6.996	0.07
Second tube row, last four columns	7.07	0.07	other columns	7.12	0.07
Third tube row, last four columns	7.15	0.07	other columns	7.28	0.071

- Equal distribution of volumetric flow – bulk velocity of the flue gas is equal in the area outside of the tube bundle.
- Amount of the steam in the tubes is constant.
- Steam distribution into the collector is equal.
- Simplifying of bifurcation of a pipe at membrane wall connections.
- In the analytical calculation is the membrane wall considered to be only simple support.

All these factors may influence the calculated vibration results. Damaging to the steam boiler as a non–continual process has to be also considered.

3.4 CFD and FSI analysis

In the next step analytically calculated results were verified by numerical analysis (CFD and FSI). The analysis of steam distribution to individual tubes into the collector was performed in order to examine the possibility of non-uniform flow. The initial differences in steam distribution were equalized to minimal differences over the analysis time. Next, the simulations of flue gas flow in non tubed spaces were performed. Those analyses confirmed the vortex creation and their excitation, which induces vibrations of the tubes (Figure 5, Figure 6). The vortexes are induced behind the body of the tube and they are asymmetrically detached. It results in harmonically variable loads of the tubes in a boundary layer. This excitation has the same frequency as the natural frequency of the tubes. The mechanism is not necessarily present all the time because of variations during the operation of the boiler. The last series of analyses was performed by FSI. The analyses proved harmonically variable load on tubes, but did not confirm sufficiently the deformation which could lead to crack initiation and propagation. Nevertheless, the character of deformation indicates the possibility of the high cycle fatigue appearance.

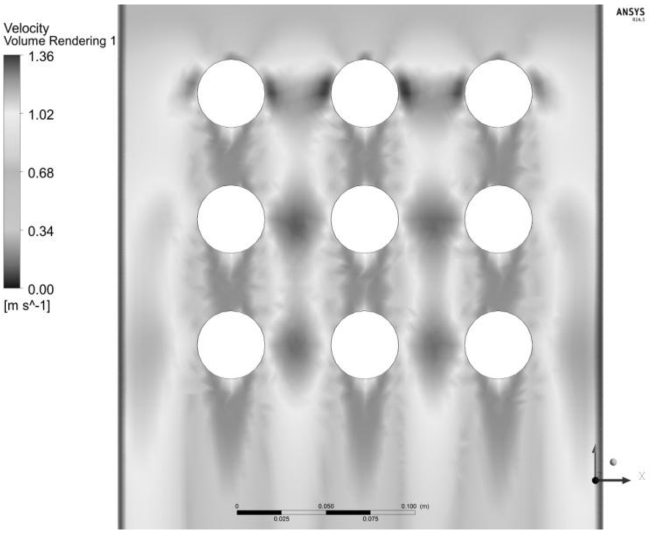

Figure 5: Flue gas velocity

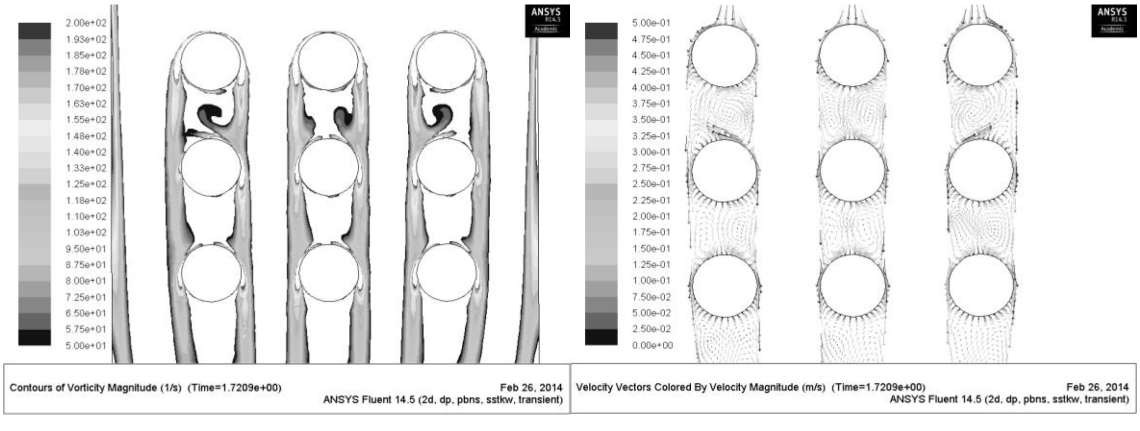

Figure 6: Flue gas vortex magnitude, Flue gas velocity vector magnitude

4. Future work

Further investigation will continue after shut down of the boiler and closer examination of the cracks surface character. If the material samples prove the character of damage mechanism described in the article, geometry modification using the impingement baffles for flue gas stream modification design will be performed. It has to be designed with respect to the retaining heat transfer value of the tube bundle. If the material elaboration of the samples do not confirm failure mechanism, new series of analysis with respect to new data will be performed.

5. Conclusions

The study of collector damage performed by means of analytical and numerical analyses confirmed the possibility of crack initiation and its further development in the area between collector nozzles. The results confirmed that vibrations caused by flow of the flue gas are probably the main reason of damage. Vibration of tubes is induced by vortex excitation and acoustic resonation. Although the results of analyses are indicating to vibration as the main cause of collector damage, closer examination and further numerical analyses will be necessary after shut down of the boiler and after the closer examination of the samples. Meanwhile, it is necessary to manufacture a new collector which replaces the current one during the shutdown. Due to this fact, design modification of the collector was proposed on the background of performed analyses. This article describes series of numerical and analytical analyses which identified damage mechanism which was high cycle fatigue. During the operation, the crack occurrence is in the interval of four to five years, which is in compliance with considered damage mechanism. Analytical analyses were used to determine the additional boundary conditions which were used by numerical analyses. The most important analysis was the fluid induced vibration analysis, which confirmed the occurrence of vibrations induced by vortex excitation and acoustic resonation.

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