Article

An Analysis of a Reheater Failure and a Proposal to Upgrade the Device Design

Piotr Duda 1,*, Łukasz Felkowski 1, Adam Zieliński 2 and Andrzej Duda 1

1 Institute of Thermal and Process Engineering, Cracow University of Technology, Al. Jana Pawła II 37, 31-864 Kraków, Poland; lukasz.felkowski@gmail.com (L.F.); andrzej.duda@pk.edu.pl (A.D.)
2 Institute for Ferrous Metallurgy, ul. K. Miarki 12-14, 44-100 Gliwice, Poland; azielinski@imz.pl
* Correspondence: pduda@mech.pk.edu.pl; Tel.: +48-12-6283401

Received: 10 May 2019; Accepted: 7 June 2019; Published: 13 June 2019

Abstract: The aim of this paper is to present an example of damage to the reheater tubes and conduct the material and numerical analyses to establish the cause of the device failure. Cracks were observed on the first, second, and third tube row. Close to the damaged area, a ferritic structure could be observed with highly degraded bainite areas, characterized by coagulation and coalescence of precipitates. The cause of the damage was analysed using the finite element method (FEM). The big yield of the tube cross-section confirmed that the tube may get damaged during subsequent cycles of the boiler operation, which was also proved by the microstructure testing results. For the reheater under analysis, the tubes have to be lengthened to achieve a reduction in stresses, arising due to thermal loads to values lower than allowable stresses according to Standard EN 13480-3. The modelling results confirmed the correct operation for the upgraded system.

Keywords: reheater; rupture; microstructural degradation; failure analysis

1. Introduction

Boiler installations built in the 1990’s are more and more often operated under a higher risk of damage to pressure elements. Due to the time of to-date service, and the large number of shutdowns and start-ups, the number of failures has been on the rise annually [1–4].

Power station turbines are subject to considerable thermal loads. The most common type of fatigue damage in turbines manifests itself in cracks appearing in the blade [1]. The detection of cracks by means of the current monitoring system is difficult, even if they are very large. Additionally, a combination of low-cycle and creep fatigue is the main factor resulting in the failure of many critical components in the power plant infrastructure. To predict fatigue life under different experimental conditions, various conventional life-prediction models are evaluated and discussed [2]. Thermal expansion, high pressure, and temperature also shorten the life of reheaters and superheaters [3].

Such a failure of the reheater tubes occurred in June 2018 in a boiler unit in Poland. A visual inspection, material testing and numerical modelling were carried out to verify the failure mechanism and identify the root cause of the event [4].

The reheater damaged tubes operated for about 190,000 h under variable thermal and pressure-related operating conditions. The tubes were connected to the header on one side; on the other, they went through a membrane wall, with a temperature higher than that of the header. The thermal stresses, resulting from such a connection, often create problems to the boiler operation. Design standards usually define the procedure for designing tubes with respect to the steam pressure value only. The impact of thermal expansion on stress values is resolved by the designer [5,6]. Similar failures occurred in boiler installations previously [7], but it is only recently that they have been investigated in detail. Considering that the service life of professional boilers in Poland has now reached nearly
200,000 h, such failures can be expected to occur more often. As the standards followed in the design of such systems were inadequate, special attention should be paid to cooperating elements and the entire system should be appropriately modernized to prevent more frequent failure-related shutdowns to the boiler. To improve the functioning of devices, numerical modelling is often used. A numerical study on flow characteristics in a Francis turbine, during load rejection, is presented in [8]. A multi-scale flow study is of great significance in understanding the effect of the clearance flow on the load rejection process in the Francis turbine. The multi-objective function of the boiler combustion system and the multi-objective optimization model were established using the improved distributed extreme learning machine algorithm to reduce NOx emissions and improve the boiler combustion efficiency [9].

The aim of this paper is to present examples of damage to the reheater tubes and conduct the material and numerical analyses, in order to establish the cause of the failure. A proposal is also made for modernization, so as to reduce stress intensification.

2. Visual Inspection

A diagram of the system under consideration is shown in Figure 1. The visual inspection, performed after the boiler was cooled down, revealed considerable deflection of the reheater tubes, as presented in Figure 2.

Figure 1. Power boiler diagram with the place of failure (Detail A) 1—reheater header (Ø711 × 45 mm); 2—reheater tubes (Ø44.5 × 4.5 mm); 3—feed pipeline; 4—pipeline hangers; 5—device preventing displacement and rotation on the pipeline-header interface; 6—device preventing the header displacement in direction x.

Figure 2. Visual inspection of the reheater tubes in the place where they go through the membrane wall. 1—reheater tubes, 2—membrane wall, 3—header, 4—insulation

Figure 3 shows a diagram, which includes the measurements for the presented state. Cracks were observed on the first, second, and third tube row. A fragment of a damaged tube is presented in Figure 4. The damage was found only where the reheater tubes went through the membrane.
wall. The tubes and the header are made of 10CrMo9-10 steel. 44.5 × 4.5 mm tubes are welded to a Ø711 × 45 mm header. Un-tightness was also noticed in the area where the tubes were welded to the header.

3. Material Testing

The tube material chemical composition was established using an emission spectrometer. The tube material was verified as 10CrMo9-10 steel [10]. The tested chemical composition is given in Table 1.

Table 1. The tested chemical composition % for 10CrMo9-10.

| C   | Mn  | Si  | P   | S   | Cu  | Cr  | Ni  | Mo  | Other |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|
| 0.092 | 0.47 | 0.30 | 0.011 | 0.014  | 0.073  | 2.30  | 0.21  | 1.02  | 0.007  |

A visual inspection of the rupture area was carried out (Figure 4). The strength tests were performed in room temperature, according to Standard EN-ISO 6892-1 [11]. The testing results are listed in Table 2. The stress-strain curve was plotted (Figure 5). The specimens were sampled from beyond the damage area presented in Figure 4.
Table 2. Results of strength testing performed in room and elevated temperature.

| Tested Element | Steel Grade       | Testing Temperature (°C) | Strength Properties |       |
|----------------|-------------------|--------------------------|---------------------|-------|
|                |                   |                          | $R_m$ (MPa) | $R_{eH}$ (MPa) | $A_5$ (%) |
| Tube section   | 10CrMo9-10        | 20                       | 422 (440 min) | 225 (265 min) | 25 (20 min) |
|                |                   | 500                      | 283                  | 192 (186 min) | 27          |

Figure 5. Stress-strain curve at the temperature of: 20 °C and 500 °C.

The values of the tensile strength and the yield stress ($R_m$, and $R_{eH}$, respectively), obtained from post-operation testing in room temperature of the specimen made of 10CrMo9-10 steel, are lower compared to the required minimum value for the analysed steel grade in the initial state after normalizing and tempering according to Standard EN 10216-2 [12].

The microstructure was tested using an Inspect F scanning electron microscope (SEM) on conventionally prepared nital-etched metallographic micro-sections. The tested specimen structure is presented in Figures 6 and 7. It can be seen that at a distance of about 300 mm from the detected discontinuity, there is a ferritic-bainitic structure with only slightly degraded areas of bainite and numerous, very fine precipitates inside the ferrite grains, as well as fine precipitates along the grain boundaries (Figure 6). Close to the damaged area, however, where the allowable (design) stress-and-strain values are exceeded considerably, a ferritic structure can be observed with highly degraded bainite areas, characterized by coagulation and coalescence of precipitates. Numerous precipitates with sometimes a considerable size (1–2.5 µm) occur along the grain boundaries (Figure 7).
Table 2. Results of strength testing performed in room and elevated temperature.

| Tested element | Steel grade | Testing temperature (°C) | Strength properties |
|----------------|-------------|--------------------------|---------------------|
| Tube section   | 10CrMo9-10 | 20 422 (440 min) 225 (265 min) 25 (20 min) 500 | Rm 283, ReH 192 (186 min) A5 27 |

Figure 5. Stress-strain curve at the temperature of: 20 °C and 500 °C.

Figure 6. Tested steel specimen structure in a place beyond the detected damage.

The microstructure was tested using an Inspect F scanning electron microscope (SEM) on conventionally prepared nital-etched metallographic micro-sections. The tested specimen structure is presented in Figures 6 and 7. It can be seen that at a distance of about 300 mm from the detected discontinuity, there is a ferritic-bainitic structure with only slightly degraded areas of bainite and numerous, very fine precipitates inside the ferrite grains, as well as fine precipitates along the grain boundaries (Figure 6). Close to the damaged area, however, where the allowable (design) stress-and-strain values are exceeded considerably, a ferritic structure can be observed with highly degraded bainite areas, characterized by coagulation and coalescence of precipitates. Numerous precipitates with sometimes a considerable size (1–2.5 μm) occur along the grain boundaries (Figure 7).

Figure 7. Tested steel specimen structure in the immediate vicinity of the detected discontinuity.

4. Damage Algorithm

The cause of the damage was analyzed using the finite element method (FEM) and by taking account of real operating conditions. The diagram in Figure 8a presents the top view of the boiler wall, tubes and header in the cold state (20 °C). The boiler operating parameters are reached (383 °C—the boiler wall; 500 °C—the boiler header and tubes). The FEM analyses took account of steady-state operation, omitting the fatigue phenomena. Deformation of the system occurred as shown in Figure 8b. The deformation was found during observation of the operation of the header and of the tubes, and it was also confirmed in the initial FEM analyses. The coefficients of thermal expansion were adopted in accordance with Standard EN 13480-3 [6]. For a temperature range between 300 °C and 500 °C this coefficient is $\alpha = 1.35 \times 10^{-5} / 1.41 \times 10^{-5} °C^{-1}$.

First, a global analysis of the system presented in Figure 1 was performed taking account of one-dimensional (1D) elements and by using the Auto Pipe software [13]. The analysis was based on the linear material model. The highest-stress concentration zones were localized and the values of forces and moments were read out.
4. Damage Algorithm

The cause of the damage was analyzed using the finite element method (FEM) and by taking account of real operating conditions. The diagram in Figure 8a presents the top view of the boiler wall, tubes and header in the cold state (20 °C). The boiler operating parameters are reached (383 °C—the boiler wall; 500 °C—the boiler header and tubes). The FEM analyses took account of steady-state operation, omitting the fatigue phenomena. Deformation of the system occurred as shown in Figure 8b. The deformation was found during observation of the operation of the header and of the tubes, and it was also confirmed in the initial FEM analyses. The coefficients of thermal expansion were adopted in accordance with Standard EN 13480-3 [6]. For a temperature range between 300 °C and 500 °C this coefficient is \( \alpha = 1.35 \times 10^{-5}/1.41 \times 10^{-5} \, ^\circ\text{C}^{-1} \).

First, a global analysis of the system presented in Figure 1 was performed taking account of one-dimensional (1D) elements and by using the Auto Pipe software [13]. The analysis was based on the linear material model. The highest-stress concentration zones were localized and the values of forces and moments were read out.

![Diagram of the boiler wall-tubes-header system](image)

**Figure 8.** Diagram of the boiler wall-tubes-header system (top view): (a) cold state (shutdown); (b) hot state (operation)

Based on the global analysis results, stress concentration zones were indicated as in Figure 9. The results taking account of pressure and deadweight only are presented in Figure 9a. The allowable stress values are not exceeded. Next, a change in the system temperature was analyzed. Different temperatures of the boiler tubes and header operation, compared to the boiler wall, caused a non-uniform expansion of the system, which led to high stresses, as shown in Figure 9b. The stress concentration zones correspond to the locations of the system rupture.

![Fragment of the global system](image)

**Figure 9.** Fragment of the global system under the highest stress-and-strain values taking account of: (a) loads from pressure \( P \) and deadweight; (b) thermal expansion; allowable stresses according to Standard EN 13480-3 for the standard value of yield stress \( R_p = 186 \, \text{MPa} \).
The non-linear analysis was conducted using the Ansys program, which allows for the proper selection of the material model and more advanced calculations [14]. The numerical global model, presented in Figure 10, is built of 117,666 elements. It contains solid elements (tubes in the place of plasticization), the shell (header) and 1D elements (tubes in which stresses are below the yield point). The areas of the biggest yield of the tubes were localized by means of a non-linear 3D analysis [14–16] using the material testing results presented in Figure 5. The analysis was carried out for the reheater fragment made of the header and tubes which is subjected to the highest stress-and-strain values. This sub-model is built of 78,015 Solid186-type elements [14] per 0.26 m³ volume of the model. The system was loaded with the forces and moments calculated in the global model. The tubes and the header were studied using the considered elastoplastic material models with a multilinear kinematic hardening case. The strains arising in the system material are expressed as:

\[ \varepsilon_{\text{tot}} = \varepsilon_e + \varepsilon_p \]  

where total strain \( \varepsilon_{\text{tot}} \) is a combination of elastic strain \( \varepsilon_e \) and plastic strain \( \varepsilon_p \). The elastic strain follows Hook’s law:

\[ \sigma = C : (\varepsilon_e) . \]  

The multilinear kinematic hardening model presumes that material hardening takes place along linear segments in a piecewise manner. For each segment, the constant hardening modulus value is defined as:

\[ H_k = \frac{d\sigma}{d\varepsilon_p} \]  

where \( \varepsilon_p \) is equivalent plastic strain.

According to the adopted non-linear material model, directional displacement, and equivalent (von Mises) stresses for the reheater tube rows are presented in Figure 10.

\[ \varepsilon_{\text{tot}} = \varepsilon_e + \varepsilon_p \]  

Figure 10. Finite element method (FEM) analysis results: (a) directional displacement (mm) and (b) equivalent (von Mises) stresses for the reheater last tube rows; measured yield stress value: \( R_{p 0.2} = 192 \) MPa

The level of stresses exceeding the yield stress correspond to the locations of the tube rupture. The stresses in the tube cross-section (Detail A in Figure 10), in the area of transition through the tight wall, are shown in Figure 11.
Figure 11. Equivalent (von Mises) stresses for a tube with an exceeded yield point; measured yield stress value: $R_{p0.2} = 192$ MPa

In Figure 11, it can be seen that the yield point is exceeded for most of the tube cross-section. Figure 12 presents plastic strain values on the tube cross-section. The plastic strain area also occupies most of the tube cross-section. Such a big yield of the tube cross-section indicates that this particular element may get damaged during subsequent cycles of the boiler operation.

Replacing the material and changing the thickness of the reheater tubes often bring no desired effects in terms of a reduction in stresses. In such a situation, the only solution is to increase the system yield strength by increasing the length of the tubes. For the reheater under analysis, the tubes have to be lengthened by 1000 mm to achieve a reduction in stresses arising due to thermal loads to values lower than allowable stresses according to Standard EN 13480-3 [6]. The results for a system upgraded in this way are presented in Figure 13. It should be added that, after the upgrade, the system header needs additional supports at the ends.
5. Conclusions

The cause of the failure was established by means of a visual inspection, material testing, and numerical modelling. The consequences of the failure were the system rupture (Figure 4) and deformation (Figures 2 and 3). Compared to Standard EN 10216-2, the material testing results point to better properties at a temperature of 500 °C, while slightly worse at 20 °C. The numerical modelling results prove that loading with deadweight and pressure does not involve exceeding allowable stress values. By taking account of thermal expansion in the analysis, it was possible to identify the most loaded areas of the system.

It is demonstrated that, in the outermost tubes, the yield point may be exceeded due to bending caused by different thermal expansions of the header and of the tubes, compared to the membrane wall. This leads to the conclusion that appropriate provisions should be made in relevant design standards [5], with particular emphasis on tube circumferential stresses (pressure-related mainly), thus omitting bending stresses from thermal expansion. Incorrect adoption of boundary conditions and the flexibility of tubes can cause their plasticization during the boiler first start-ups, which in cyclic-operation conditions, can lead to rapid destruction and subsequent repair shutdowns.

The areas of the tubes plastic deformation were localized by means of a non-linear 3D analysis, using the material testing results. The big yield from the tube cross-section confirmed that the tube may get damaged during subsequent cycles of the boiler operation, which is also proved by the microstructure testing results. They show considerable degradation of the tested steel, compared to areas where stresses higher than allowable were not found. The changes of the microstructure were described using the material characteristics, which are the basis for predicting the service life of the material of components operating under creep conditions [17,18]. In order to improve the system operation, a proposal is made to increase the system yield strength by increasing the length of the tubes. For the reheater under analysis, the tubes have to be lengthened by 1000 mm to achieve a reduction in stresses, resulting from the thermal loads to values lower than allowable stresses according to Standard EN 13480-3 [6]. The modelling results confirm the upgraded system correct operation.

Author Contributions: Conceptualization, P.D. and Ł.F.; Methodology, P.D.; Software, Ł.F. Validation, Ł.F., A.Z. and A.D.; Formal Analysis, P.D.; Investigation, Ł.F.; Resources, A.Z.; Data Curation, A.D.; Writing—Original Draft Preparation, P.D.; Writing—Review & Editing, P.D.; Visualization, A.D.; Supervision, P.D.; Project Administration, P.D.; Funding Acquisition, P.D.

Funding: This research was financed by the National Science Centre, Poland, UMO-2015/19/B/ST8/00958.

Conflicts of Interest: The authors declare no conflict of interest.
References

1. Zhang, M.; Valentin, D.; Valero, C.; Egusquiza, M.; Zhao, W. Numerical Study on the Dynamic Behavior of a Francis Turbine Runner Model with a Crack. *Energies* **2018**, *11*, 1630. [CrossRef]

2. Wang, X.; Zhang, W.; Zhang, T.; Gong, J.; Abdel Wahab, M. A New Empirical Life Prediction Model for 9–12%Cr Steels under Low Cycle Fatigue and Creep Fatigue Interaction Loadings. *Metals* **2019**, *9*, 183. [CrossRef]

3. Felkowski, Ł.; Medrala, J. Analysis of reheater tubes failure. In Proceedings of the ICBT Poland 2018—E3S Web of Conferences, Szczyryk, Poland, 23–26 October 2018.

4. Duda, P.; Felkowski, Ł.; Dobrzański, J. An analysis of an incident during the renovation work of power boiler reheater. *Eng. Fail. Anal.* **2015**, *57*, 248–253. [CrossRef]

5. Ente Nazionale Italiano di Unificazione (UNI). EN 12952-3: 2012. *Water-Tube Boilers and Auxiliary Installations. Design and Calculation of Pressure Parts*; UNI: Milan, Italy, 2012.

6. European Committee for Standardization (CEN). EN 13480-3: 2017. *Metallic Industrial Piping. Design and Calculation*; British Standards Institution (BSI): Gunnersbury, UK, 2017.

7. Sertić, J.; Kozak, D.; Konjatić, P.; Kokanović, M. Analytical and numerical investigation of elastic-plastic behavior of the connecting pipes between header and steam reheater. In Proceedings of the 6th International Congress of the Croatian Society of Mechanics, Dubrovnik, Croatia, 30 September–2 October 2009.

8. Zhou, D.; Chen, H.; Zhang, J.; Jiang, S.; Gui, J.; Yang, C.; Yu, A. Numerical Study on Flow Characteristics in a Francis Turbine during Load Rejection. *Energies* **2019**, *12*, 716. [CrossRef]

9. Xu, X.; Chen, Q.; Ren, M.; Cheng, L.; Xie, J. Combustion Optimization for Coal Fired Power Plant Boilers Based on Improved Distributed ELM and Distributed PSO. *Energies* **2019**, *12*, 1036. [CrossRef]

10. Polish Committee for Standardization and Measurement (PKNiM). PN-75/H-84024. *Steel for Working at Elevated Temperatures—Grades*; PKNiM: Warsaw, Poland, 1975.

11. International Organization for Standardization (ISO). ISO 6892-1:2016. *Metallic Materials—Tensile Testing. Method of Test at Room Temperature*; ISO: Geneva, Switzerland, 2016.

12. European Committee for Standardization (CEN). EN 10216-2: 2014. *Seamless Steel Tubes for Pressure purposes. Technical Delivery Conditions. Non-Alloy and Alloy Steel Tubes with Specified Elevated Temperature Properties*; Official Journal of the European Union (OJEU): Aberdeen, UK, 2014.

13. *Bentley Auto Pipe V8i Select Series 10 Edition Workbook*; Bentley Motors Limited: Crewe, UK, 2016.

14. ANSYS User’s Manual, Revision 19.1. Available online: [http://research.me.udel.edu/~jlwang/teaching/MEx81/ansys56manual.pdf](http://research.me.udel.edu/~jlwang/teaching/MEx81/ansys56manual.pdf) (accessed on 10 April 2019).

15. Miroshnik, R.; Shaked, Y.; Elmakis, D. Life Assessment Evaluation of piping branch connection under creep & fatigue. *Int. J. Press. Vessel. Pip.* **1997**, *71*, 147–154.

16. Matine, A.; Drissi-Habti, M. On-Coupling Mechanical, Electrical and Thermal Behavior of Submarine Power Phases. *Energies* **2019**, *12*, 1009. [CrossRef]

17. Zieliński, A.; Sroka, M.; Hernas, A.; Kremzer, M. The effect of long-term impact of elevated temperature on changes in microstructure and mechanical properties of HR3C steel. *Arch. Metall. Mater.* **2016**, *61*, 761–765. [CrossRef]

18. Golański, G.; Zieliński, A.; Zielińska-Lipiec, A. Degradation of microstructure and mechanical properties in martensitic cast steel after ageing. *Mater. Wirkstofftech.* **2015**, *46*, 248–255. [CrossRef]