

Stress analysis of the O-element pipe during the process of flue gases purification

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Abstract

Equipment for flue gases purification from undesired substances is used throughout power and other types of industry. This paper deals with damaging of the O-element pipe designed to remove sulphur from the flue gases, i.e. damaging of the pipe during flue gases purification. This purification is conducted by spraying the water into the O-shaped pipe where the flue gases flow. Thus the sulphur binds itself onto the water and gets removed from the flue gas. Injection of cold water into hot flue gases, however, causes high stress on the inside of the pipe, which can gradually damage the O-element pipe. In this paper initial injection of water into hot pipe all the way to stabilization of temperature fields will be analyzed and the most dangerous places which shall be considered for fatigue will be determined.

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1. Introduction

Removing undesired harmful substances from flue gases is a very important industrial process that is constantly being subject to research activities in order to find out new methods of flue gases purification. This is mainly caused by strict legislation on emission limits in developed countries. Among some of the undesired substances are sulphur dioxide, carbon monoxide, dioxins, solid substances, heavy metals, etc.

The Institute of Environmental and Process Engineering at Brno Technical University examined scrubbing of flue gases when sulphur was removed and thus the content of sulphur dioxide in the flue gases was lowered [1, 6]. This experiment was carried out in O-element; water was injected into the flowing flue gas and the sulphur bounded itself to the water and created sulphide. Since there was a temperature shock due to cooling of hot flue gas by cold water while carrying out this experiment, these pipes underwent a series of thermo-hydraulic and consequently stress analyses in order to determine to which extent its lifetime is lowered by these effects [3].

2. Analysis of the experiment

The O-element is made of steel 15 128 (11CrMo9-10). Material properties are given in tab. 1. The size of the pipe is 100x4. An input pipe is divided into two U-shaped pipes and there is a pipe of 69x3 with jets tangentially attached to the lower part. Through jets the water is injected into the flow of the flue gases. Two pipes merge back together at the concurrence

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Table 1. Material properties of steel 15 128 (11CrMo9-10)

T [°C]	R_e [MPa]	R_m [MPa]	E [MPa]
20	358.7	505.6	213 300
100	336.4	471.0	209 000
200	308.9	459.1	202 100

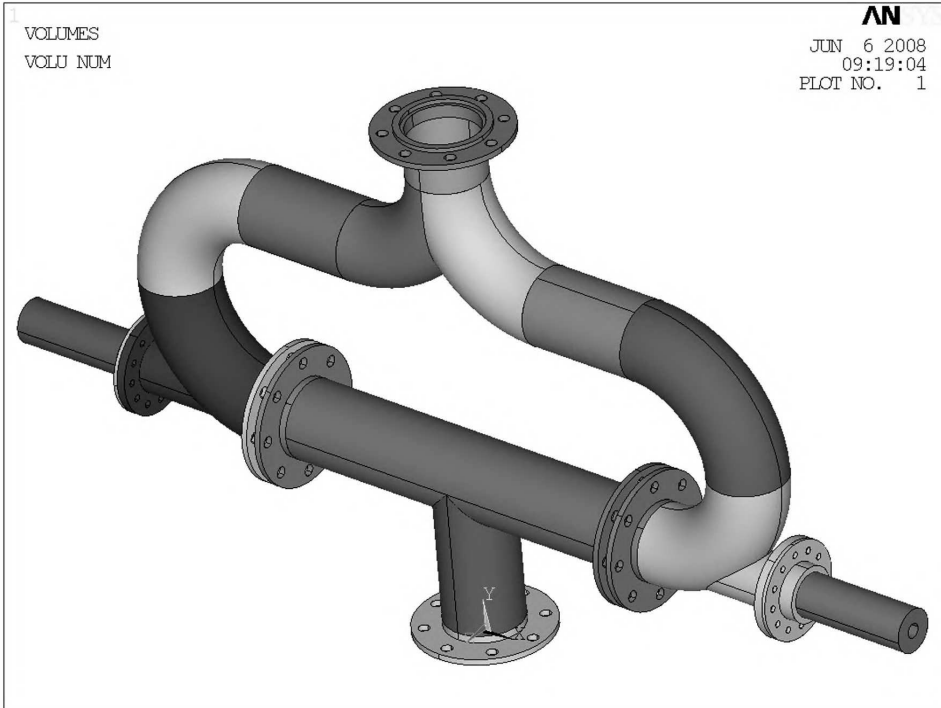


Fig. 1. Type of O-element used

of the two flows. Geometric disposition of the O-element is displayed in fig. 1. Model was slightly simplified for the purposes of numeric simulations in a sense that flanged joints were not considered.

During the flue gases purification experiments the ideal ratio of flue gases flow rate to injected water flow was searched. Flue gas flow rate changed in the range from 700 to 1 000 m_N^3/h , water flow rate varied in the range from 0.68 to 2.15 m^3/h [6]. From all analyzed variants one was chosen for numerical simulation. It corresponded to a low flue gases flow rate and the largest volume of injected water. Precisely, the value of flue gases flow rate equalled to 800 m_N^3/h and water flow rate equalled to 2.15 m^3/h . Temperature of flue gases entering the O-element equals to 200 °C, temperature of water entering nozzles equals to 20 °C. Flue gases chemical composition is given in the tab. 2 [6].

3D model of the O-element and medium was created in SolidWorks program. Calculation model was made in ANSYS program. It comprises 600 000 elements and 320 000 nodes. Mesh

Table 2. Flue gases chemical composition

	O ₂	CO ₂	H ₂ O	N ₂
Specific %	18	1.6	3	77.4

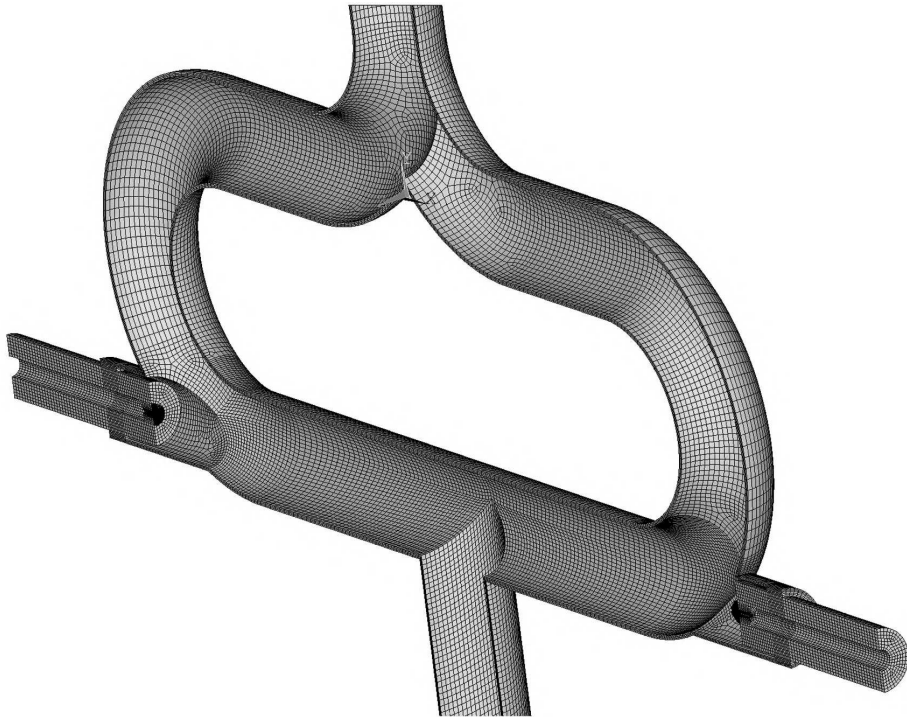


Fig. 2. Computational model of O-element for numerical analysis

of the medium was refined at the line between medium and pipe, which makes up the boundary layer. Symmetry of the model was used in order to reduce the amount of nodes and elements. Input and output pipes were modeled extendedly so that there are no interferences of important areas with boundary conditions. It also helped in developing sufficient flowing. Jets were distinctly refined (both the fluid and solid model, see fig. 2) since these are the places where liquid medium meets the gas one or cool meets the hot.

3. Procedure of Analysis

Combination of thermo-hydraulic and structural analyses is called Fluid Structure Interaction (FSI) [3]. It is in fact a task set where output data of one analysis are input boundary conditions for a different analysis. It is therefore possible to transfer data from CFD into FEM software and vice versa which was earlier done manually or via implemented procedures. Nowadays, since the CFD and FEM software are merging, there is no more need to transfer data manually as the transfer is done automatically. This, however, concerns only full versions of CFX and ANSYS programs.

As to the calculations that were done, there was not a full version of the software available, thus we transferred the data manually using CFX-Solver Manager. This was done by means of the *.res file for concrete time and for the selected volumes and surfaces. Since the temperatures in the volume of material are the most important ones, we exported temperatures of all node points using 3D Thermal elements (70) and pressure on inner pipe wall using 2D Stress elements (154). Both files were exported into a cdb format which is compatible with ANSYS program. Files contain information about coordinates, temperatures and pressures for the nodes selected.

Multiple file analysis (the so called Multifield analysis) was used for determining distribution of stress in the pipe material. This type of analysis implements several files into structural one and requires that the calculation model is in cdb format (made up of elements and nodes only, not of geometry) and boundary conditions are considered as new meshes. These new meshes have to merge with the calculation mesh so that the transfer of data from one mesh to another is possible (i.e. from thermal mesh to the structural one). Other boundary conditions such as constraints and forces are entered on node groups which were already created upon making up of the calculation model. Since all the boundary conditions are entered, it is necessary to define mutual relations between individual files, i.e. to define main model and following external files (data on temperatures and pressures). It is also necessary to define the procedure of the calculation which means that the temperature deformations are to be calculated first, then pressure deformations and only then come other boundary conditions. All this data has to be entered into one final file usable for following experiments.

4. Analysis of flow and thermal fields distribution

Models for two-phase streaming were to be used in the simulations. For the cases of dispersion (spraying) of fluid medium in gas medium it is convenient to use particles trajectory model (Euler-Lagrange principle) [4, 10]. It describes initial phase as a continuum by means of averaged Navier-Stokes equations. In a secondary phase a flying trajectory is traced for drops which can transmit momentum, mass and energy from the initial phase. The basic condition of the method sounds that secondary phase must occupy very small volume fragment, this condition is satisfied in the O-element.

K- ε model was used for turbulence [9]. Momentum transfer was realized by means of Drag Coefficient. Gas medium was entered as continuum, fluid medium was entered as dispersion with known drop size 10 μm [6]. Particle Model was used for interphase transmission. Heat transfer between flue gases and drops was described by means of Nusselt number or more precisely Ranz-Marshall correlation. Mass transfer was described by constant evaporative ratio, which was taken from the work [6]. Initiation was entered according to operating conditions of flowing fluids.

Boundary conditions were presented by inlet of water and flue gases and outlet of flue gases. Initiation was entered according to inlet conditions of flue gases. To achieve higher stability of calculation, flue gases were taken as incompressible.

Thermal-hydraulic analysis of the fluid injected into hot gas was solved as a transient case. It was necessary to choose time steps managing the whole computation. In the beginning time steps should be very small (millesimals of a second), later time steps may be increased to seconds with a gradual setting and stabilization of equations. The most important time moment when calculation may become unstable is the moment of fluid medium injection to the O-element. For this moment time steps should be minimal and the number of iterations should be sufficient for solving this unstable process.

In the beginning of the process the pipe is heated to the temperature of flue gases (200°C), when the purification process starts, cold medium (20°C) is injected. Surface layers of material experience shock changes and development of additional stresses due to different thermal expansion. During several tens of seconds thermal fields distribution is stabilized. The most significant thermal influence occurs in nozzles, precisely in sharp edges above nozzles. Based on thermal-hydraulic analysis there were chosen time moments when thermal fields distribution influences principally caused stresses.

It is obvious from the results that pressure drops take place in the place where both streams collide, moreover streaming changes its direction rapidly. Temperature of flue gases immediately after water injection is markedly lower. Volume content of fluid compared to that of flue gases is very low. Since drops flow in the same direction with flue gases, achieved results are better compared to other ways of flue gases purification (e.g. Venturi scrubber), where fluid is injected upright to the flow of flue gases [2, 7, 8].

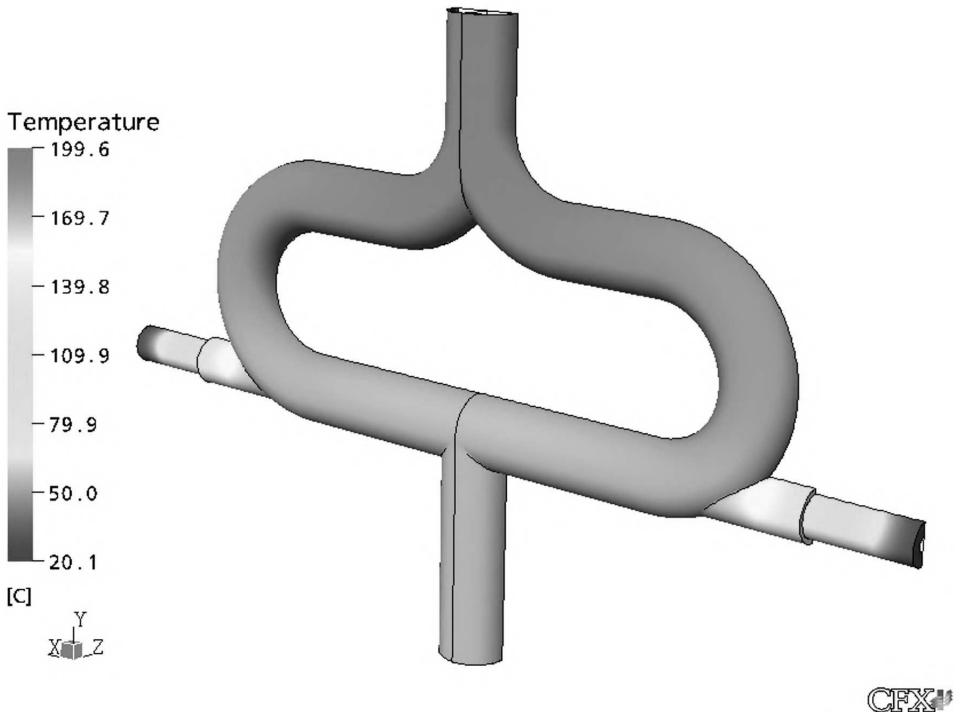


Fig. 3. Thermal field distribution

5. O-element stresses

In the region where main piping branches into two flows stresses are concentrated in the sharp connection. Stress reaches the value of 75 MPa (see fig. 4). These stresses do not change during fluid injection into the O-element, that is why this place does not play an important role in fatigue analysis. More important areas are those, where nozzles are connected to the O-element, mainly zones above nozzles, where connection is realized as a sharp edge. Stresses

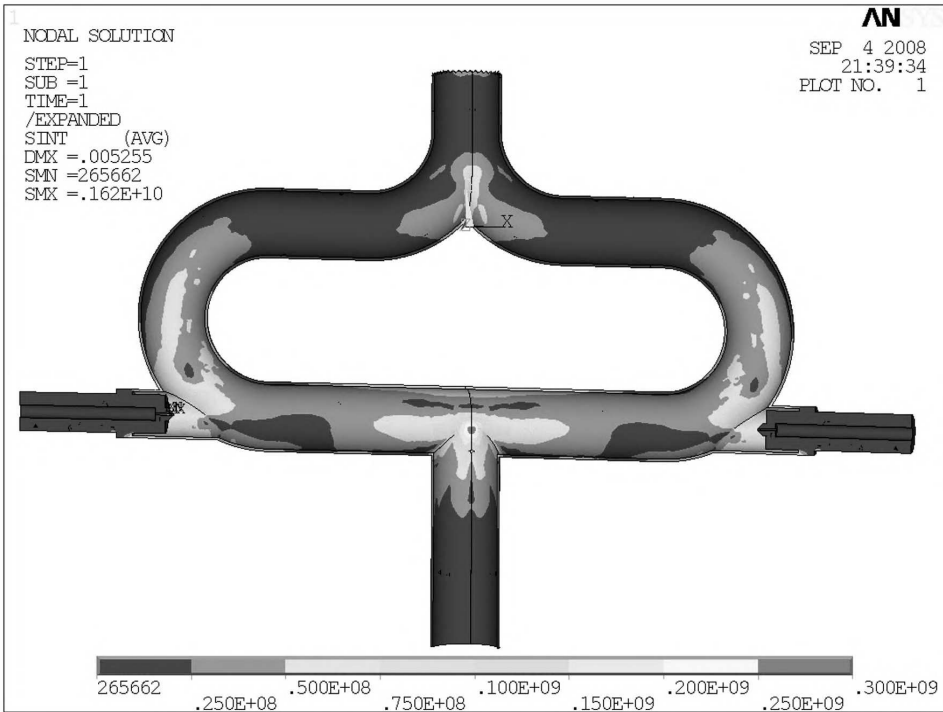


Fig. 4. Stress distribution in O-element (stress intensity)

of value cca 200 MPa appear in these zones. During cooling the amplitude is about several tens of MPa. The most critical zone is the one where a pipe for flue gases outlet is connected. Here both flows meet each other and drain into one pipe. Connection of pipes with same sizes is designed not favourably, this causes high values of stresses, locally up to 300 MPa, and near edges around 200 MPa. During cooling the amplitude is about several tens of MPa.

6. Damage of separate zones

On the basis of performed analyses for particular time moments stresses changes were determined for separate areas of the O-element during thermal fields setting. Those are principal for damage cumulation determination. There were chosen zones with maximum values of stresses, for these zones damage cumulation was determined. Fig. 4 shows clearly that significant stresses appear in the place where pipes for flue gases outlet is connected, below nozzles and in the area where main piping is divided into two flows. It is possible to say that these are the places of essential geometrical changes.

Strength analysis was conducted under condition of elastic deformation of the material within the whole load amplitude. The most loaded zones were chosen according to the results of strength analysis and, due to the low value of stresses high-cycle fatigue was considered. Their location can be seen in the fig. 5. FEM analyses were carried out in the ANSYS program.

Calculation of damage from mechanical fatigue including its accumulation was carried out in the program STATES. Fatigue accumulation was calculated for high-cycle fatigue using Wöhler curve (fig. 6) [5]. Stress safety factor $n_\sigma = 1.5$ and cycle number safety factor $n_N = 3$

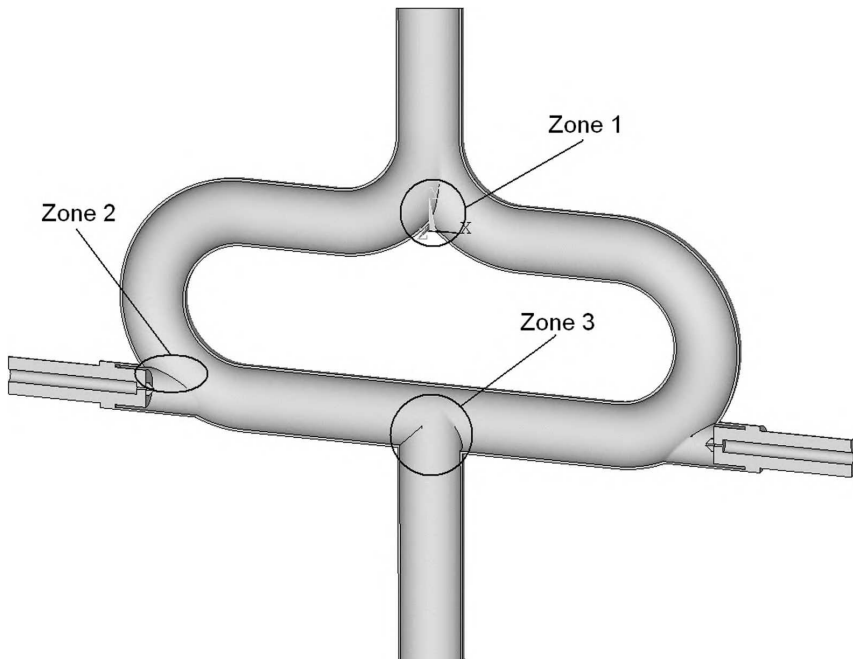


Fig. 5. The most loaded zones

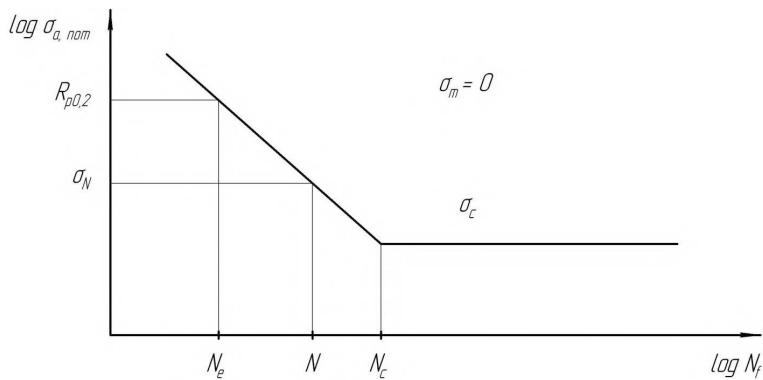


Fig. 6. Wöhler's curve for high-cycle fatigue

were used. The zones chosen earlier were evaluated; cyclic load for them was derived from the process of streams setting. Each zone was represented by the most loaded points. Resultant cumulation of damage is shown in the tab. 3 and corresponds to the load from one cycle.

Table 3. Table of cumulation for separate zones

	Zone 1	Zone 2	Zone 3
Cumulation [-]	0	0.000 1	0.000 3

7. Conclusion

Flue gases purification is interesting not only from chemical processes point of view, but also from mass change point of view as well as from thermal loading point of view. To solve the problem there was used the combination of computational methods so called FSI (Fluid Structure Interaction). The most demanding stage was two-phase flow simulation which takes place when cold water is injected into hot flue gases. It was very important to input correct values of computational model and different parameters.

CFD results showed that heat exchange between flow gases and water drops took place almost immediately. It was also found out that this way of flue gases purification does not involve so high values of pressure drops and is more efficient compared to other types of purification. Determined thermal field distribution made it possible to find out stress state. This was done in ANSYS software for particular time moments. Stress changes were analyzed and the most loaded zones were determined. They were analyzed from high-cycle fatigue point of view further on.

Components of stress tensor and their changes in particular zones were used for high-cycle fatigue analysis. The results showed that damage cumulation in all zones is neglectable. It is possible to state that for such loading conditions the O-element will endure unlimited number of injections of water into flowing hot flue gases.

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References

- [1] J. Buchta, M. Filip, L. Bébar, P. Stehlík, M. Šarlej, New design in off-gas clearing systems supported by experimental and computational approach, *Chemical Engineering Transactions* 7 (2005) 375–380.
- [2] G. F. Hewit, *Heat exchanger design handbook*, Begell House, Inc., New York, 1998.
- [3] S. Chapuliot, C. Gourdin, T. Payen, J. P. Magnaud, A. Monavon, Hydro-thermal-mechanical analysis of thermal fatigue in a mixing tee, *Proceedings of Fatigue of reactor components*, Proceedings on CD ROM, Seville, 2004.
- [4] C. Kleinstreuer, *Two-phase flow, Theory and applications*, New York, London, Taylor & Francis, 2003.
- [5] T. H. G. Megson, *Structural and stress analysis*, Oxford, 2000.
- [6] M. Piskovský, *Modelling of equipment used in waste combustion and off-gas cleaning systems*, Ph.D thesis, Brno university of technology, Brno, 2008.
- [7] M. Piskovský, J. Hájek, P. Stehlík, Computational fluid dynamics simulation of venturi wet scrubber, *Proceedings of the 17th International Congress of Chemical and Process Engineering CHISA 2006, 9th Conference on Process Integration, Modeling and Optimisation for Energy Saving and Pollution Reduction PRES 2006*, Proceedings on CD ROM, Prague, 2006.
- [8] R. A. Pulley, Modeling the performance of venture scrubbers, *Chemical Engineering Journal* 67 (1) (1997) 9–18.
- [9] T. H. Shih, W. W. Liou, A. Shabbir, Z. Yang, J. Zhu, A new $k-\varepsilon$ eddy-viscosity model for high Reynolds number turbulent flow — model development and validation, *Computers Fluid* 24 (3) (1995) 227–238.
- [10] P. B. Whalley, *Two-phase flow and heat transfer*, Oxford, New York, 1996.