Analysis of the influence of internal forces and moments on the nozzle of the main downcomer of a steam boiler drum

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Abstract: *The present work deals with the analysis of the influence of internal forces and moments on the nozzle of the main boiler of a steam boiler used in the waste incineration industry. The analysis is carried out analytically by performing calculations using standards, and later numerically using finite element method software. As results of the analyses, equivalent von Mises stresses, displacements and buckling eigenvalues are obtained and compared with analytical solutions.*
Keywords*: STEAM BOILER, DOWNCOMER, NOZZLE, FINITE ELEMENT ANALYSIS*

1. Introduction

A steam boiler is an object in which the heat energy obtained by the combustion of organic fuels is transferred by means of heating surfaces to the liquid that evaporates in it and whose vapor is superheated to a certain temperature. [1]

Steam boilers are an integral part of many plants, including waste-to-energy (WTE) plants. Boilers for waste-to-energy plants are usually water tube boilers and usually have four passes: three vertical radiant passes and one convective pass. The first of the radiant passes is integrated into the furnace as an afterburner chamber. The convective pass, which houses the evaporators, superheaters, and economizers, can be vertical or horizontal. [2]

Boilers for waste systems are drum boilers, characterized by a drum. The drum is a large high-pressure cylinder of water located in the upper part of the boiler that physically separates the evaporation of the water from the superheating of the steam. The water circulates naturally over the downcomers and up through the evaporator tubes because the evaporated water (steam) has a lower density than the water in the downcomers. [3]

It is very important to ensure the safe operation of steam boilers, and standard calculations and inspections of all parts of the boiler object are required to verify and confirm safety. This also applies to the downcomers of the WTE boiler under consideration, the structure of which is shown in Figure 1.

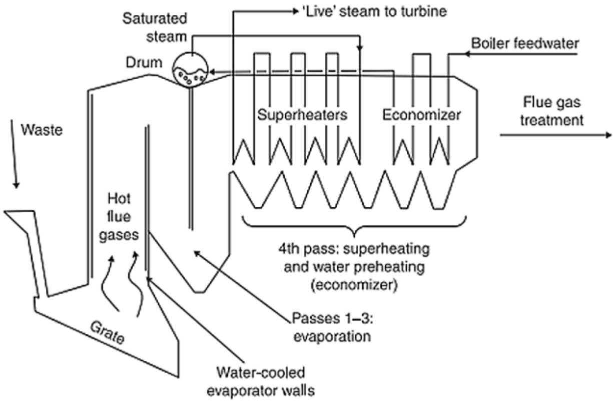

Fig. 1 *Four-pass WTE boiler [3]*

2. Problem description

To ensure safe operation of the steam boiler, the parts of the steam boiler and its supporting structure must be designed and tested using existing standards, and other means, including finite element analysis where required and applicable. Steam boiler downcomers are common and important parts of steam boilers used in the waste incineration industry, and they are connected to the drum of the steam boiler through nozzles. Therefore, safe operation of the above parts must be ensured.

The main focus was on the study of the influence of internal forces and moments on the nozzle of the main downcomer (Figure 2), which together with other loads and boundary conditions act on the mentioned component, in order to analyze its stability. This influence was analyzed analytically using the European standards. A 3D model of the structural part was created and the numerical calculation was also performed in Abaqus CAE. [4]

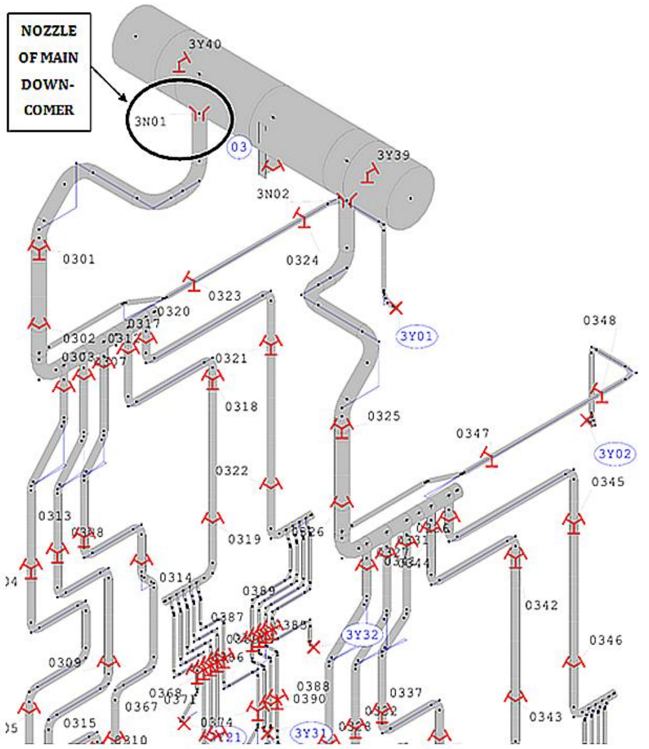

Fig. 2 *Downcomers of a steam boiler drum [5]*

3. Analytical calculation using EN 13445-3

In general, the standard EN 12952-3 [6]: 'Water-tube boilers and auxiliary installations - Part 3: Design and calculation for pressure parts of the boiler" is used for water-tube steam boilers, i.e. also for drums. However, this standard assumes in its chapter 8.3.2.1, which considers openings, including nozzles of downpipes, that external forces and moments acting on the nozzle are insignificant. If this is not the case, EN 13445 should be used to calculate and evaluate the resulting stresses.

Therefore, the third part of this standard, EN 13445-3 [7]: 'Unfired pressure vessels - Part 3: Design', is used for this calculation.

In addition to this standard, the following standards are also used: EN 10028-2 [8]: 'Flat products made of steels for pressure vessels - Part 2: Unalloyed and alloyed steels with specified properties at elevated temperatures" and EN 10216-2 [9]: 'Seamless steel tubes for pressure vessels - Technical delivery conditions - Part 2: Unalloyed and alloyed steel tubes with specified properties at elevated temperatures".

Figure 2 shows the boiler drum with all its downcomers. As shown in the figure, the main downcomer bears the designation 3N01. The input data were determined in accordance with EN 13480 [10] and presented in the form of calculation results of the internal forces and moments at the nozzle of the main downcomer (Table 1).

***Table 1** Calculation results of downcomers according to the EN 13480*

Node	Displacement, mm			Force, kN			Moment, kN·m		
	w_x	w_y	w_z	Q_x	Q_y	Q_z	M_x	M_y	M_z
3N01	-	12,6	-9,6	-20,4	-2,1	-29,4	50,4	103,6	52,3
3N02	-	-12,6	-9,6	-20,4	2,1	-29,4	-50,4	103,6	52,3

Section 16.5 of EN 13445-3 provides a method for the design of a cylindrical shell with a nozzle subjected to local loads and internal pressure. In this calculation, the standard has been worked through its subsections. The sequence is as follows:

1. Calculation of allowable stresses of shell material and nozzle material,
2. Calculation of the conditions of applicability,
3. Calculation of maximum allowable individual loads (allowable pressure, allowable axial nozzle load, allowable circumferential and longitudinal moments),
4. Calculation of the combination of external loads and internal pressure (individual load ratios, interaction of all loads),
5. Calculation of stress ranges and their combination and
6. Calculation of nozzle longitudinal stresses (maximum longitudinal tensile stress, longitudinal stability of the nozzle). [7]

All calculations meet the conditions from the standard and are presented in related investigation [11] and due to the scope of the analytical calculation are not shown here.

4. Numerical analysis

For finite element method (FEM) analysis, a 3D model of the considered part of construction of a steam boiler was modelled in Abaqus CAE. Dimensions of model are obtained from technical documentation as well as loads, constraints and boundary conditions from previous investigation. [5]

Due to symmetry only one half of the drum shell geometry has been modelled: half of cylindrical shell with diameter of 2130 mm, one support (with saddle) and one nozzle of main downcomer. Model of geometry has been modelled as a 3D-shell model (Figure 3).

The material properties of the steels 15NiCuMoNb5-6-4 and 16Mo3 required for the finite element analysis are determined for the calculation temperature of 303°C according to EN 10216-2, for the required wall thickness by means of linear interpolation and fed into the material model. The material properties for 15NiCuMoNb5-6-4 are: E = 182,98 GPa, $R_{p0,2}$ = 354,2 MPa, v = 0,3 and for 16Mo3 the material properties are: E = 182,98 GPa, $R_{p0.2}$ = 172,2 MPa and v = 0,3.

Analyzed part of construction of a steam boiler drum consists not only of material of shell and nozzle, but also of material of pipelines inside the drum. Inner pipelines and isolation material are omitted in this analysis to simplify to the model, but an added material has been introduced in order to take into account influence of the additional materials as well as water inside the structure.

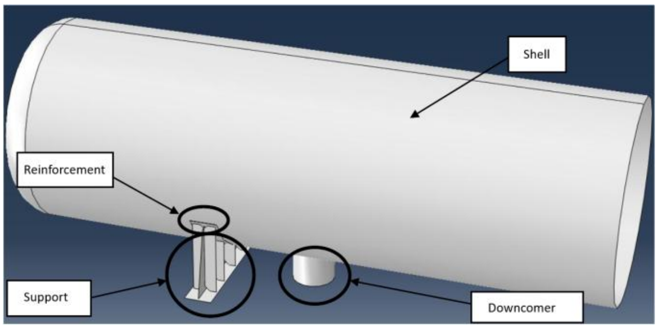

***Fig. 3** 3D-shell model used for finite element analysis*

Beside material, in this modulus, sections of supporting construction have been defined as well as section thickness. Along with defining general step, a linear perturbation step was required in order to perform buckling analysis. Using interaction modulus contacts and constraints were defined as well (Tie Constraint, Rigid Body constraint). Construction was loaded with provided load (forces and moments, friction forces, acceleration of gravity, pressure) and boundary conditions (movement restriction in x and z direction, symmetry). Model is meshed with coarse mesh with size of elements of 25 mm. Finer mesh is defined on the nozzle where shell meets the downcomer (Figure 4).

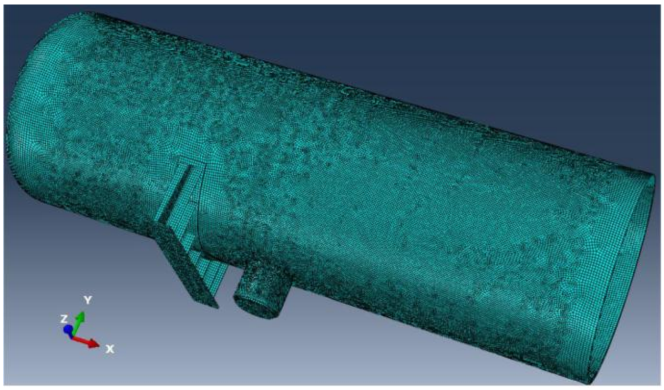

***Fig. 4** 3D-shell model used for finite element analysis*

Shell element type has been used for whole construction. Results convergence has been conducted in order to check proper sizing of defined mesh to meet required accuracy. At the end, results in form of stresses, displacements and buckling eigenvalues have been obtained.

5. Results and discussion

An analysis of the influence of forces and moments on the connection of the main downcomer also considers dealing with the main drum parts under pressure.

After conducted finite element analysis described in previous chapter, equivalent von Mises stress distribution is obtained (Figure 5). It can be noted that the maximum stress occurs on the drum, i.e. exactly on the connection of the main downcomer with its value of 498,73 MPa.

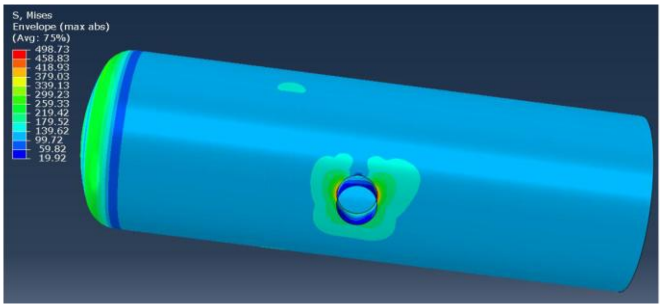

Fig. 5 *Distribution of equivalent von Mises stress on pressure parts of drum construction in MPa*

According to EN 13445-3, ANNEX 3, part C.7.3, the maximum stress is the range of equivalent stresses resulting from the changes in primary and secondary stresses ($(\Delta\sigma eq)_{P+Q}$. By definition, primary stresses are those stresses that satisfy the equilibrium laws of the given loads (pressure, forces and moments). Thus, they are caused by internal forces and moments required to balance external forces and moments.

Secondary stresses are stresses that are a consequence of constraints due to geometric discontinuities, the use of materials with different modulus of elasticity under the action of external loads, or constraints due to different thermal expansions. Therefore, they cause internal forces and moments required to satisfy the specified constraints.

The range of equivalent stresses resulting from the primary and secondary stresses, i.e., those that balance the external forces and moments and those that satisfy the specified limitations, is the maximum stress determined by the finite element analysis. This combination of stresses gives $(\Delta\sigma_{eq})_{P+Q}$ stress defined in [7] with value of $(\Delta\sigma_{eq})_{P+Q}$ = 498,73 MPa. According to [7] this stress cannot exceed triple value of allowable stress obtained by reducing yield load with safety factor, which is fulfilled in this situation.

Distribution of equivalent von Mises stress on the support is shown on Figure 6. It can be noted that maximum equivalent stress is lower than allowable stress of (116,47 MPa). Allowed von Mises equivalent stress on the support is obtained via yield strength and safety factor 1,5.

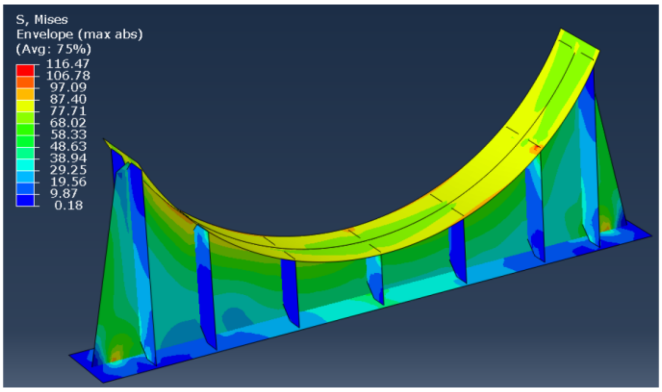

Fig. 6 *Distribution of equivalent von Mises stress in drum support in MPa*

Total displacements due to load, self-weight and pressure are presented on Figure 7 where can be noted that maximum value of displacement is under 4 mm.

As result of the buckling analysis obtained using finite elements so-called eigenvalue ("Eigen Value") is obtained. It represents the buckling factor. This factor is a value that indicates by how many times the load must be increased to cause buckling. In this case, this value is -1,79 (Figure 8). Therefore, the condition that absolute value of buckling factor must be greater than one is fulfilled.

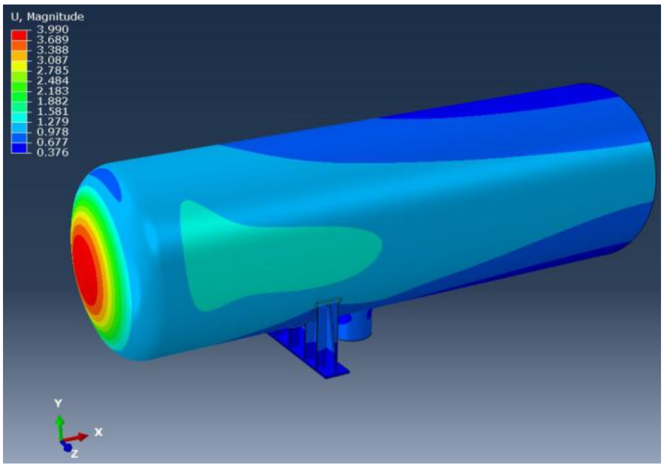

Fig. 7 *Distribution of total displacement in mm*

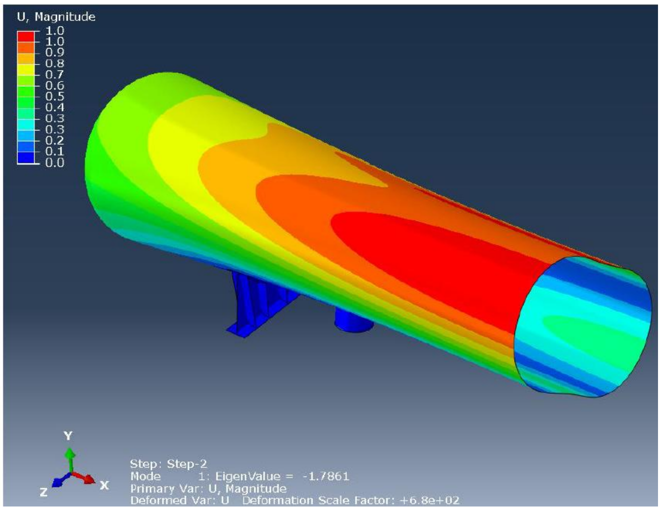

Fig. 8 *Distribution of Eigenvalue in buckling analysis*

This means that there is no risk of buckling due to the action of the internal forces and moments, gravity and pressure load on the connection of the main downcomer pipes. Buckling would only occur if the load were increased by 1,79 times. A negative value occurs for vessels under pressure and indicates that buckling would occur if the pressure acted in the opposite direction, i.e., if the vessel was subjected to excessive external pressure, i.e., vacuum.

6. Conclusion

After the analytical and numerical analysis of the critical parts in steam boiler construction, the connection of the steam boiler drum with the main downcomer is analyzed analytically using the existing standards and numerically using the finite element method.

Using the whole finite element model of the steam boiler, loads, internal forces and moments are determined and later used as boundary conditions and loads for the shell 3D finite element model of the connection between the drum and the main downcomer.

According to the performed analysis, it can be concluded that the stresses occurring in the expected operation of the critical parts of the steam boiler structure are within the allowable values for the steam boiler drum and the supporting structure.

A local stress concentration occurred at the connection between the drum and the downcomer. This stress intensity does not exceed the maximum stress defined in the standard EN 13445-3, ANNEX 3, part C.7.3.

Finally, a buckling analysis of the shell model of the drum-downcomer connection with support was performed. This analysis has shown that there is no risk of buckling due to the action of internal forces and moments, gravity and compressive load on the connection of the main pipes of the downcomer.

7. References

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