MECHANICS AND CONTROL
Vol. 29 No. 3 2010

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NUMERICAL METHOD FOR DETERMINING ALLOWABLE MEDIUM TEMPERATURE DURING OPERATION OF STEAM GATE VALVE

SUMMARY

Construction elements of power blocks such as collectors, separators or steam valves work in hazardous environment. During start-up and shut-down operations they are exposed to sudden temperature and pressure changes, that cause high stresses at certain points. Additionally, the cyclic character of loading causes material fatigue, known as low-cyclic fatigue, which may lead to the formation of fracture. Manufacturers of steam boilers provide instructions for heating and cooling processes in order to operate safely. It is important to find the optimum parameters for heating and cooling operations, i.e. parameters that enable to conduct heating and cooling in the shortest time and keep the maximum stresses in the construction within allowable limits. Efforts are made to develop an appropriate method for determining optimum operating parameters during start-up and shut-down phase of the power units. In this paper two optimum parameters will be found. Based on these parameters heating and cooling processes will be carried out and compared with heating and cooling operations processed according to the German boiler regulations Technische Regeln für Dampfkessel 301 (TRD).

Keywords: *thermal stresses, steam boilers, heat transfer, optimization*

METODA NUMERYCZNA DO WYZNACZANIA DOPUSZCZALNEGO PRZEBIEGU TEMPERATURY CZYNNIKA PODCZAS PRACY ZASUWY PAROWEJ

W pracy przedstawiono metodę do wyznaczenia takiego przebiegu temperatury czynnika, aby maksymalne naprężenia cieplne powstające podczas rozruchu lub odstawiania bloku energetycznego nie przekraczały naprężeń dopuszczalnych. Przy założeniu liniowej postaci przebiegu temperatury czynnika poszukiwane są dwa parametry. Przebiegi naprężeń cieplnych uzyskane przy nagrzewaniu lub ochładzaniu, przeprowadzonych według zaproponowanej metody, porównane są z przebiegami uzyskanymi na podstawie Niemieckiej Normy Technische Regeln für Dampfkessel 301 (TRD).

Słowa kluczowe: *naprężenia cieplne, kocioł parowy, transfer ciepła, optymalizacja*

1. INTRODUCTION

The heating and cooling operations of power block devices cause high stresses in the entire construction elements. These operations are carried out in a manner that stresses originated from the inner pressure and the temperature gradient through the wall do not exceed the allowable stresses.

The initial fluid temperature and the rate of the temperature change have great impact on stress distribution over the entire construction element. These parameters can be evaluated using the German boiler code Technische Regeln für Dampfkessel 301 (TRD) (TRD 1986). The TRD 301 procedure is based on the quasi-steady one dimensional temperature distribution in the whole component. However, the heating and cooling processes are transient operations, and the quasi-steady state does not occur. Thus, operations conducted, using parameters estimated according to TRD 301 code may account for the state, where the maximum allowable stresses are exceeded. Furthermore, complicated geometry of the components cause difficulties in assessment of the highest stress regions. Paper (Taler and Dzierwa 2007) presents the method for determining optimum medium temperature, which ensures that the sum of thermal stresses and stresses caused by pressure at selected points do not exceed the allowable stresses. Paper (Duda and Dwornicka 2008) shows the numerical method based on the golden search method, which could be used to find the optimum medium temperature so that the maximum thermal stresses in the whole construction element would not exceed the allowable stresses.

The aim of this paper is to present the method, which optimizes simultaneously both parameters: initial fluid temperature and the rate of temperature change, so that the thermal stresses are kept at an acceptable level. For that purpose the Levenberg-Marquardt method is used (Seber and Wild 1989; Taler and Taler 2009).

One of the most heavily loaded components of the power block devices is steam gate valve (SGV). The geometry of the SGV is presented in Figure 1.

This component is mounted on fresh and pre-heated steam pipelines in the power units of 360 MW. It is installed in the steam pipeline of BP1150 boiler with a steam capacity of 1150 t/h. The aggressive working environment cause high stresses in the element. The SGV is designed for the pressure p_w = 18 MPa and the steam temperature T_w = 540 °C. Extreme working conditions of the SGV require employing special alloy steels in the construction. The material applied must withstand high working temperature and pressure while operating. It is important that the material properties are retained within the wide temperature range, especially at the yield strength R_e.

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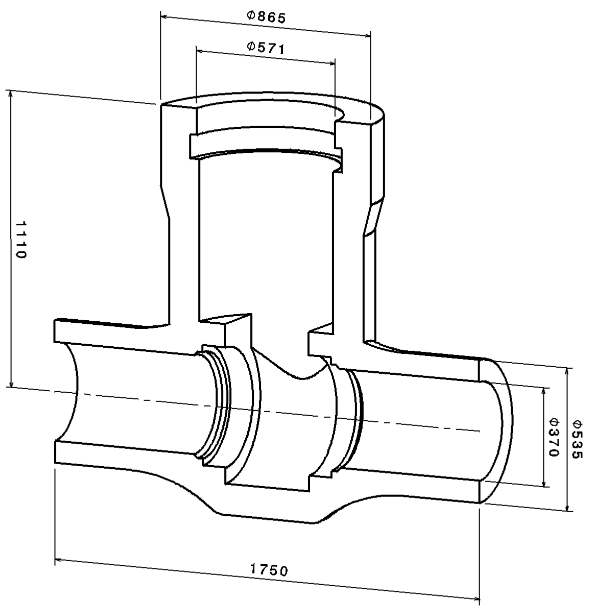

Fig. 1. Geometry of the steam gate valve in mm

The alloy steel 14MoV63 (13 HMF) is widely used for the construction of the power block devices. This steel has a ferritic structure and high yield strengths R_e = 206 MPa at the temperature T = 500 °C. The thermal and mechanical properties are presented in Figures 2 and 3 (Richter 1983).

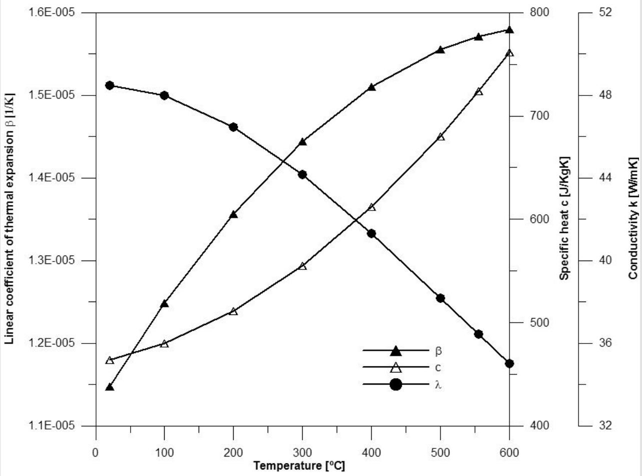

Fig. 2. Thermal properties for the steel 14MoV63

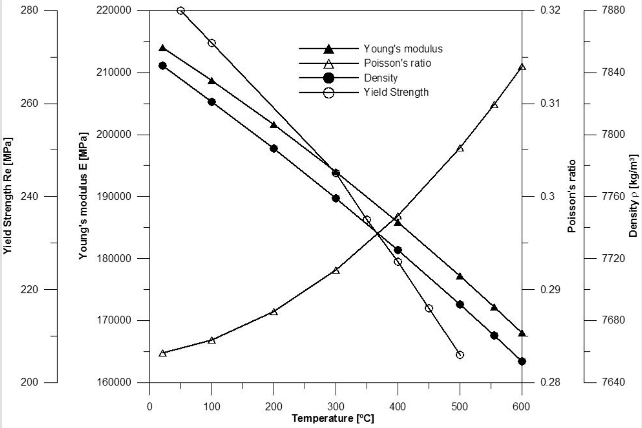

Fig. 3. Mechanical properties for the steel 14MoV63

2. THE PROPOSED NUMERICAL METHOD

Heating and cooling operations lead to formation of the high stress concentration area on the inner surface of the steam gate valve (SGV). During start-up the fluid enters the inner space of the construction element. It has initial temperature T_{f_0} and then changes with constant rate of temperature change v_T until the working temperature T_w is reached. During shut-down operation the inner space is flooded by fluid which has initial temperature T_{f_0} lower than the working temperature T_w. The object is to choose the optimum parameters, i.e. the optimum initial fluid temperature T_{f_0} and the optimum rate of temperature change v_T such that the heating and cooling operations are conducted in the shortest time and the maximum stresses $\sigma_{\max}$ are kept within acceptable limits.

Thus, the parameters T_{f_0} and v_T are found when the following equation is satisfied:

$$\sigma_a - \sigma_{\max}(T_{f_0}, v_T, t_i) \cong 0, \quad i = 1, ..., m \tag{1}$$

where m denotes the number of time points during the heating and cooling process, σ_a denotes maximum stress allowed. In other words, minimizing the sum

$$S(x) = \sum_{i=1}^{m} \left[\sigma_a - \sigma_{\max}(T_{f_0}, v_T, t_i)\right]^2 \cong 0, \; i = 1, ..., m \tag{2}$$

allows to establish the optimum parameters T_{f_0} and v_T.

Due to the nonlinear character of the considered problem the appropriate method must be chosen. In this instance the Levenberg-Marquardt method is used. The parameters updation at every kth iteration step is performed based on the following rule

$$\mathbf{x}^{(k+1)} = \mathbf{x}^{(k)} + \boldsymbol{\delta}^{(k)} \tag{3}$$

The unknown parameters of $\mathbf{x}$ are denoted as $x_1 = T_{f_0}$, $x_2 = v_T$, where

$$\boldsymbol{\delta}^{(k)} = \left(\mathbf{H}^{(k)} + \lambda \mathrm{diag}\mathbf{H}^{(k)}\right)^{-1} \left(\mathbf{J}^{(k)}\right)^T \left[\sigma_a - \sigma_{\max}\left(x^{(k)}\right)\right], \tag{4}$$

$k = 0, 1, ...$

The $\mathbf{H}$ and $\mathbf{J}$ are called Hessian and Jacobian matrices, respectively. They can be expressed in the following way

$$\mathbf{J}^{(k)} = \left.\frac{\partial \sigma_{\max}(x)}{\partial x^T}\right|_{x=x^{(k)}} = \left.\begin{bmatrix} \frac{\partial \sigma_1}{\partial x_1} & \cdots & \frac{\partial \sigma_1}{\partial x_n} \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ \frac{\partial \sigma_m}{\partial x_1} & \cdots & \frac{\partial \sigma_m}{\partial x_n} \end{bmatrix}\right|_{x=x^{(k)}} \tag{5}$$

and

$$\mathbf{H}^{(k)} = \left. \frac{\partial^2 \sigma_{\max}(x)}{\left(\partial x^T\right)^2} \right|_{x=x^{(k)}} = \left. \left[\begin{matrix} \dfrac{\partial^2 \sigma_1}{\partial x_1 \partial x_1} & \cdots & \dfrac{\partial^2 \sigma_1}{\partial x_1 \partial x_n} \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ \dfrac{\partial^2 \sigma_m}{\partial x_n \partial x_1} & \cdots & \dfrac{\partial^2 \sigma_m}{\partial x_n \partial x_n} \end{matrix} \right] \right|_{x=x^{(k)}} \tag{6}$$

The solution for optimum parameters is obtained if the assumed convergence criterion

$$x_i^{(k+1)} - x_i^{(k)} \le \varepsilon, \quad i = 1, \ldots, n \tag{7}$$

is fulfilled.

3. COMPUTATIONAL EXAMPLE

In order to perform thermal strength analysis, during heating and cooling operations, Ansys software was used. This is the engineering software package based on the finite element method (FEM).

Taking advantage of symmetry of the steam gate valve (SGV), 1/4 of the model was analyzed. Division into finite elements is depicted in Figure 4.

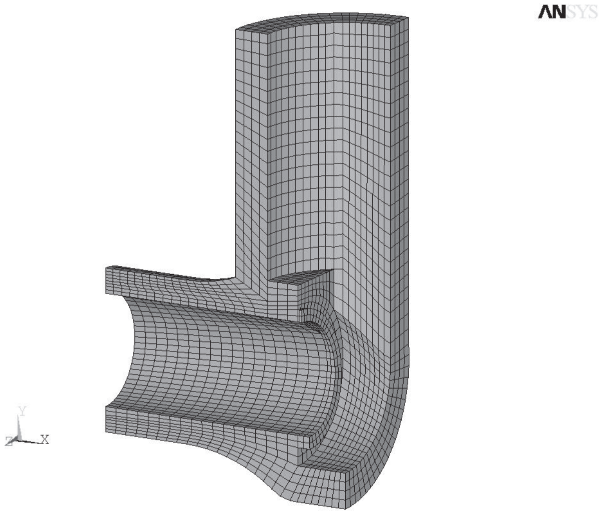

Fig. 4. Steam gate valve model divided into eight-node bricks element

The type of elements used in the analysis are eight-node finite bricks element. This type of elements guarantees good quality results in a relatively short period of time. Material properties for the SGV are presented in Figures 2 and 3. The heat transfer coefficient on the heated surface equals 2000 W/(m^2·K). The boundary condition on the outer surface of the SGV are described by the eq. (8)

$$\left. \left[k(T) \frac{\partial T}{\partial r} \right] \right|_{r=r_0} = 0 \tag{8}$$

where k is the thermal conductivity of the material, and $\partial T/\partial r$ is the temperature gradient. There is no heat exchange between the component and the environment. This indicates perfect insulation on that surface.

4. THERMAL-STRENGTH ANALYSIS ACCORDING TO TRD REGULATIONS

Heating operation based on TRD regulations

German boiler code, Technische Regeln für Dampfkessel 301 (TRD), describe a method for determination of allowable rates of temperature change for cylindrical shells. These cylindrical shells work under internal pressure whereas the temperature and pressure changes during start-up and shut-down processes. In consequence the material is subjected to combined thermo-mechanical load, that causes stresses in the structure. Therefore, the aim of TRD regulations is to calculate the allowable rates of temperature change so that stresses do not exceed the allowable stresses σ_a. Since, this paper presents the method for optimization of heating and cooling operations based on the thermal stresses, stress analysis during heating and cooling processes conducted according to TRD regulations takes only thermal loads into account. Thus, the stresses inside the structure come only from the temperature gradient through the thickness of the wall.

TRD 301 regulation assumes a quasi-steady, one dimensional temperature distribution through the wall of the construction element. According to the German boiler code the steam gate valve (SGV) has before start-up a temperature of value 20 °C and is equally distributed in the entire volume. Next, the fluid temperature inside the component rises with allowable rates of temperature change v_{T_1} = 3.17 K/min and v_{T_2} = 5.43 K/min until working temperature is achieved as shown in Figure 5. Allowable stresses for this steel for heating operation based on TRD 301 code equal σ_a = –188 MPa.

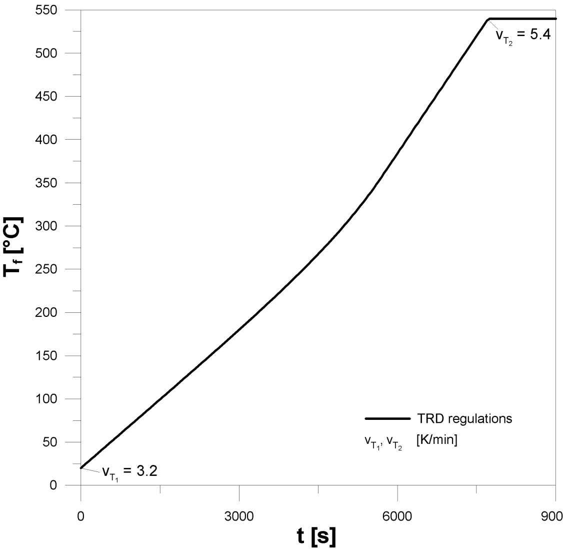

Fig. 5. Fluid temperature history during heating process according to TRD

During start-up operation high thermal stresses vary with time as illustrated in Figure 6.

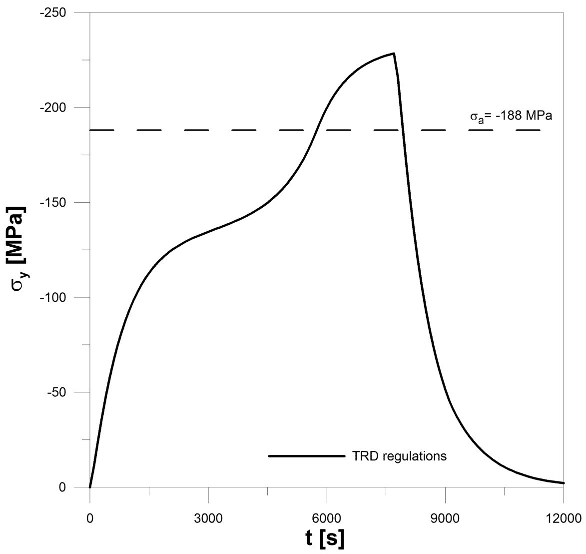

Fig. 6. Thermal stress σ_y history during heating process based on TRD regulations

It can be seen from Figure 6 that the allowable stresses σ_a are exceeded which has an impact on the longevity of the component. There is considerable thermal stresses drop after time t = 7700 s which indicates reached working parameters. Temperature distribution in the SGV at the time point t = 7700 s, where maximum stresses occurred, is plotted in Figure 7.

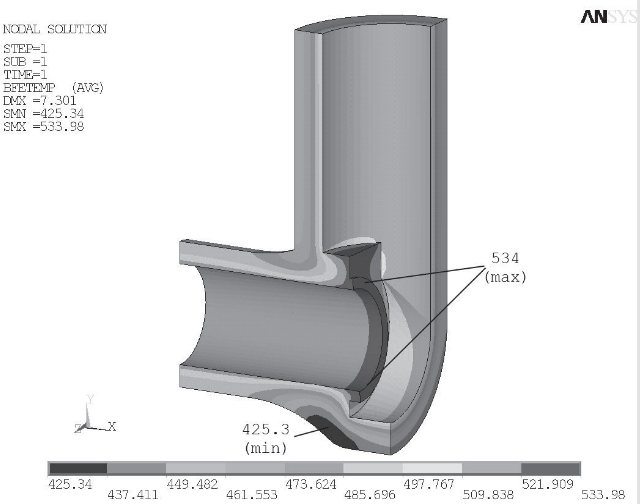

Fig. 7. Temperature distribution in ^{o}C during heating operation at time t =7700 s

The highest thermal stresses were recorded on the inner surface acting in y-direction as shown in Figure 8.

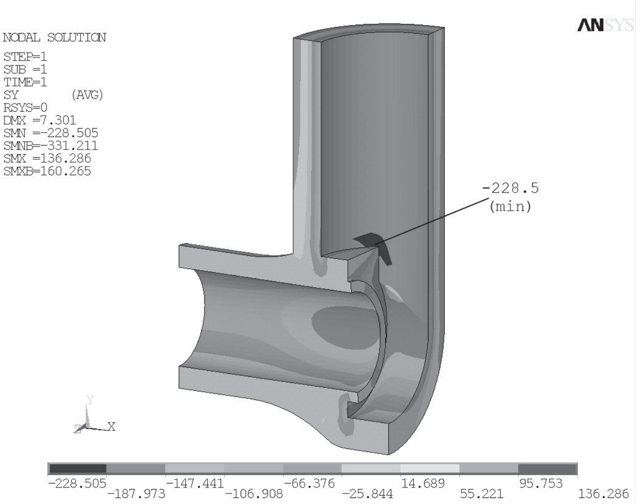

Fig. 8. Thermal stress σ_y distribution during heating process based on TRD regulations

Cooling operation based on TRD regulations

As presented in previous section heating operations induce high thermal stresses on the inner surface of the steam gate valve (SGV). These thermal stresses are considerably reduced after quasi-steady state is achieved i.e. after the time where the steam gate valve reached the nominal working temperature T_w = 540 ^{o}C.

The technical condition of the components mounted in power plants must be inspected in some time intervals which is regulated by the European Union law. For inspection purposes the power block must be shut-down. Shut-down operations cause high thermal stresses due to the temperature drop inside the component. It is important to perform the cooling process in such way that allowable stresses σ_a are not exceeded. In this section shut-down operation conducted in conformance with TRD 301 regulation is described.

Steam gate valve operates at the working temperature T_w = 540 ^{o}C uniformly distributed inside the body. Next, the SGV is cooled from inside with the allowable rates of medium temperature change v_{T_1} = –3.17 K/min and v_{T_1} = –5.43 K/min, prescribed by TRD regulations (Fig. 9).

The allowable stresses for cooling operation given by TRD equal σ_a = 321 MPa. The cooling procedure is carried on until the SGV reaches the ambient temperature. The thermal stresses induced by the fluid temperature change are presented in Figure 10.

It can be noted from Figure 10 that the maximum thermal stresses are below the allowable stresses value σ_a. This gives us the safety margin and ensures that the component is not thermally overloaded. Nevertheless, the cooling process is extended in time which is undesirable effect. The temperature distribution at the time point t = 7600 s is plotted beneath (Fig. 11).

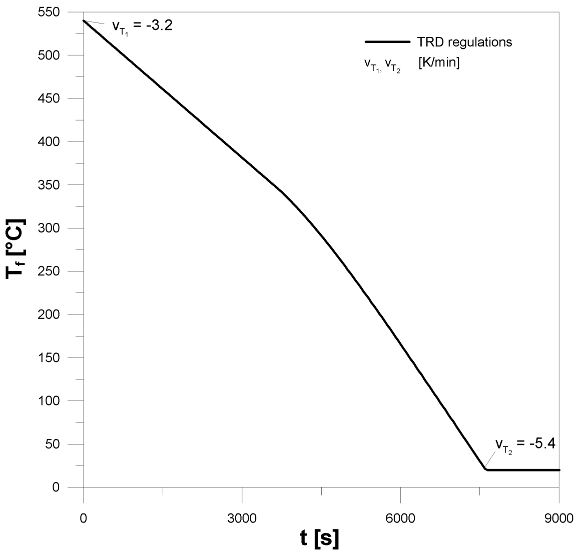

Fig. 9. Fluid temperature history during cooling process according to TRD

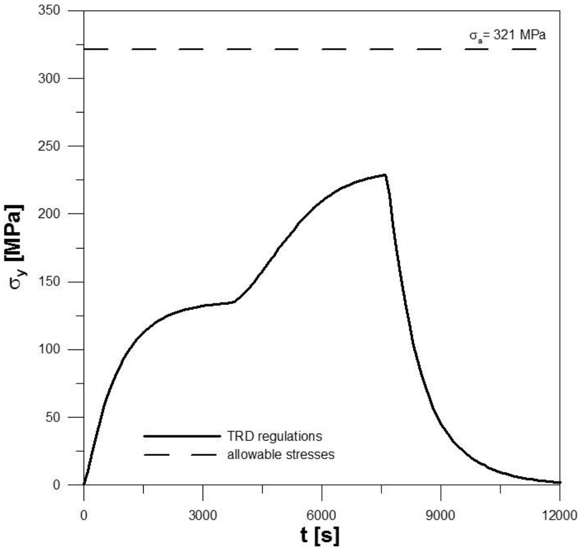

Fig. 10. Thermal stress σ_y history during cooling process based on TRD regulations

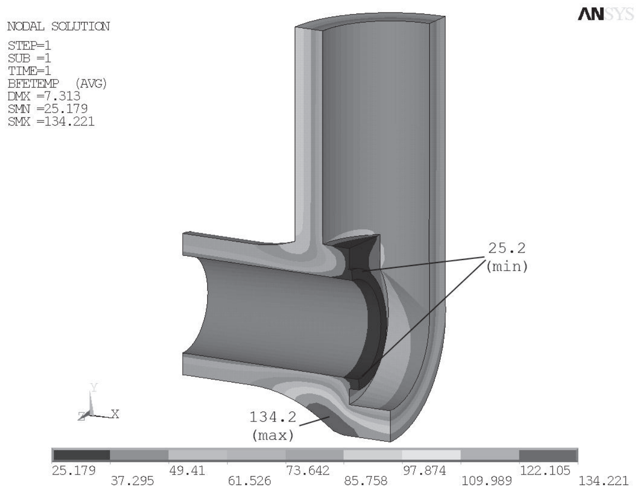

Fig. 11. Temperature distribution in °C during cooling operation at time t = 7600 s

Figure 12 presents the maximum thermal stresses observed at the time t = 7600 s.

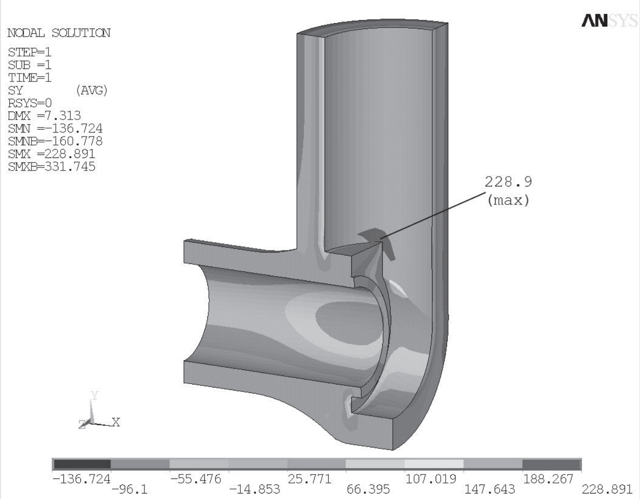

Fig. 12. Thermal stress σ_y distribution during cooling process at time t = 7600 s based on TRD regulations

5. THERMAL-STRENGTH ANALYSIS BASED ON LEVENBERG-MARQUARDT OPTIMIZATION METHOD

Heating operation based on Levenberg-Marquardt optimization method

In previous chapter heating and cooling operations of the steam gate valve (SGV) according to TRD regulations were covered. It was shown that during start-up process the allowable stresses σ_a are exceeded (Fig. 6). On the other hand cooling operation conducted in accordance with German boiler code TRD 301 assures that the highest thermal stresses stay far below the stress limit, providing greater margin of safety. However, this causes shut-down process extended in time. This section presents new developed numerical method which allows to establish optimum parameters during operation of power block devices. The method presentes is based on the Levenberg-Marquardt optimization algorithm.

Let's assume the hot fluid flooding the inner space of the SGV that has an initial temperature T_{f_0} higher than the component temperature. Subsequently, the fluid is heated-up with a constant rate of temperature change v_T approaching the working temperature T_w. The goal is to find the optimum parameters T_{f_0} and v_T provided that the allowable stresses σ_a are not exceeded. The solution for the optimum parameters converged after 9th iteration. Optimum initial fluid temperature T_{f_0} = 82.4 °C and optimum rate of temperature change v_T = 4.4 K/min were found. The optimal fluid temperature transient is presented in Figure 13.

The performed thermal stress analysis brought out that the maximum stresses work in y-direction. For the optimum working parameters i.e. T_{f_0} and v_T, the highest thermal stresses σ_y are observed short after fluid gets in contact with the inner surface so at the beginning of the heating process. The stress history during this operation is presented in Figure 14.

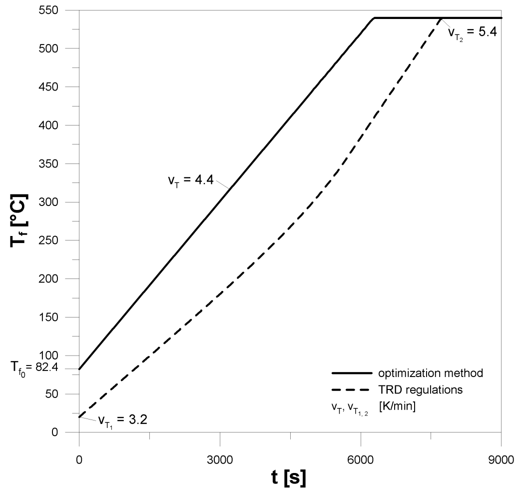

Fig. 13. Optimum fluid temperature history during heating process

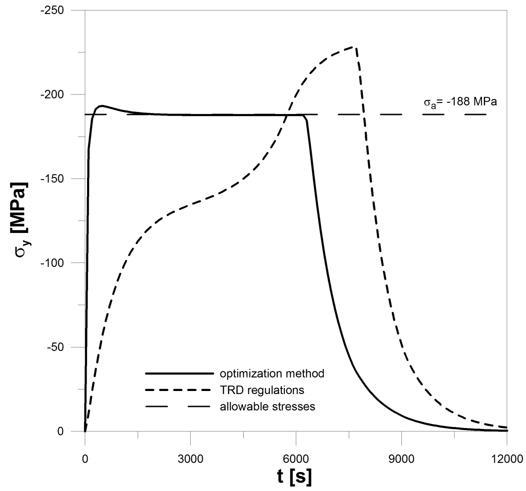

Fig. 14. Thermal stress σ_y history during heating process based on optimization method in comparison with TRD regulations

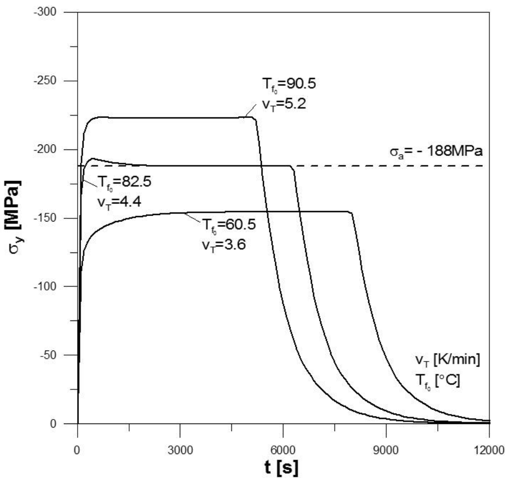

Fig. 15. Thermal stress histories for different initial fluid temperatures and rates of temperature change

Once the initial fluid temperature T_{f_0} and temperature change rate v_T are higher than optimum, the allowable stresses are exceeded (Fig. 15).

Temperature distribution inside the component at time t = 500 s is shown in Figure 16.

Figure 17 presents thermal stress σ_y distribution inside the SGV at the beginning of the heating process for optimum working parameters.

Thermal stresses acting in different direction are presented in Figures 18 and 19.

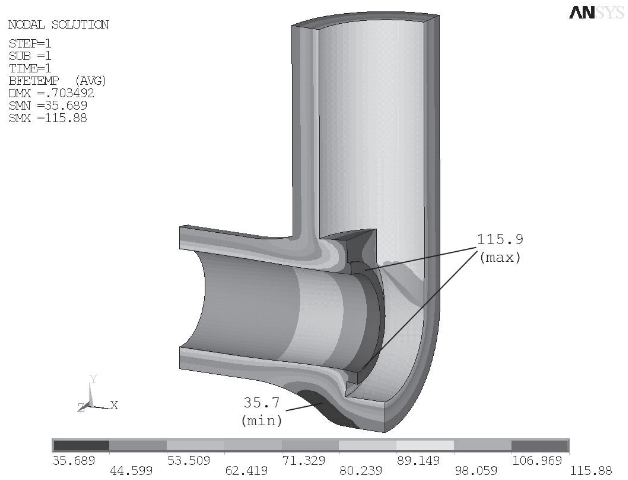

Fig. 16. Temperature distribution in °C after t = 500 s

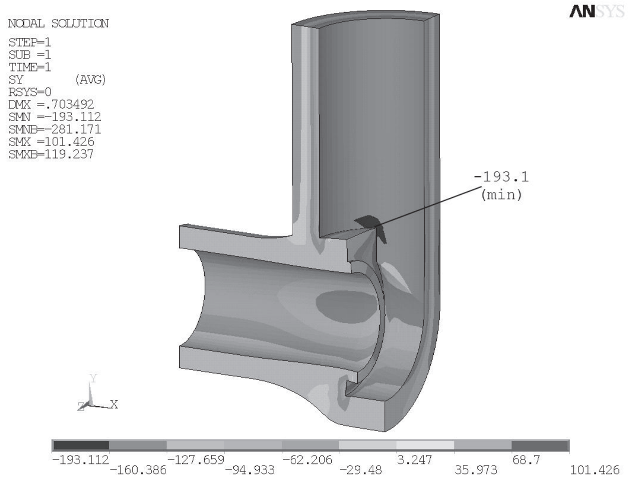

Fig. 17. Thermal stress σ_y distribution in MPa for t = 500 s

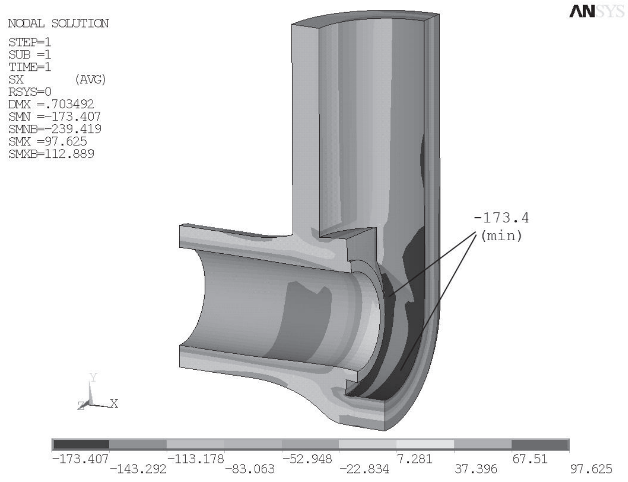

Fig. 18. Thermal stress σ_x distribution in MPa for t = 500 s

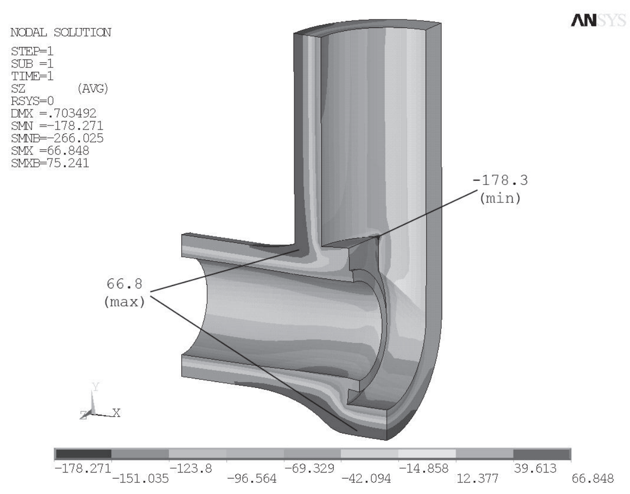

Fig. 19. Thermal stress σ_z distribution in MPa for t = 500 s

Cooling operation based on Levenberg-Marquardt optimization method

The steam gate valve (SGV) operates at the nominal working temperature T_w = 540 °C. Now, consider fluid entering the steam gate valve with the initial temperature T_{f_0} lower than working temperature T_w. Subsequently, the fluid temperature is decreased with the constant rate of temperature change ν_T. The object is to find parameters T_{f_0} and ν_T such that the cooling operation could be performed within shortest period of time and the permitted stresses σ_a = 321 MPa calculated according to TRD 301 code (Technische Regel für Dampfkessel) are not exceeded. The parameters T_{f_0} = 450 °C and ν_T = 6.0 K/min were used as the starting values in the optimization algorithm. After 12 iteration the following parameters T_{f_0} = 433.3 °C and ν_T = 7.5 K/min were found as optimum parameters. The history of optimum ν_T together with optimum T_{f_0} are presented in Figure 20.

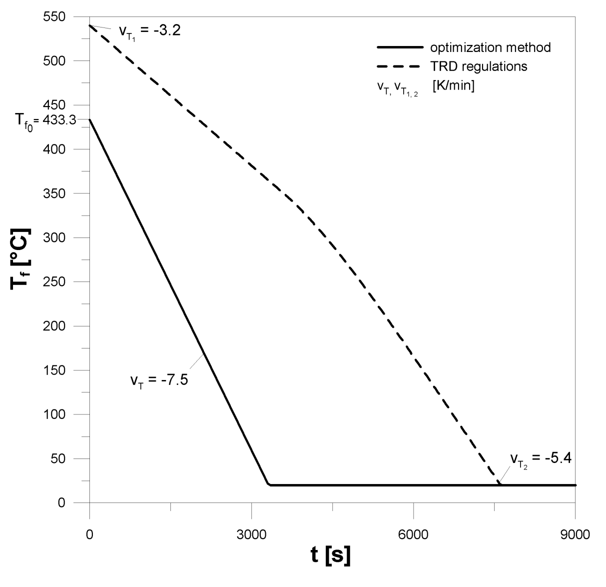

Fig. 20. Optimum fluid temperature history during cooling process

Due to the temperature gradient in the element wall, high thermal stresses are recorded inside the SGV. The finite element analysis showed that the maximum stresses occurred after fluid entered into the SGV. The highest stresses act along y-direction. The stresses variation within time is shown in Figure 21.

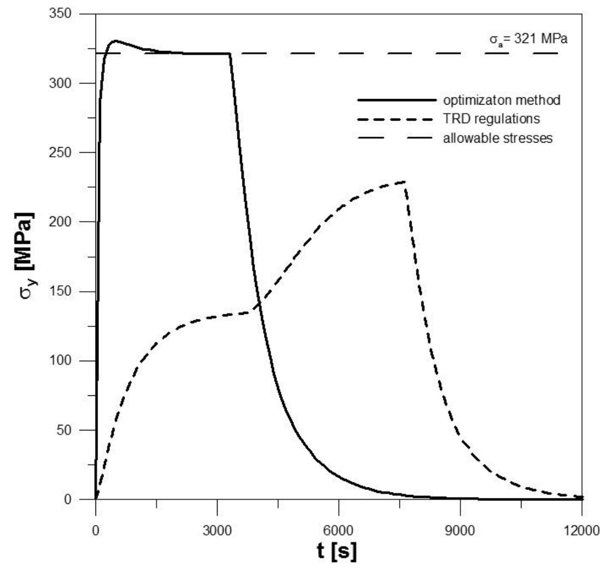

Fig. 21. Thermal stress σ_y history during cooling process based on optimization method in comparison with TRD regulations

The level of thermal stresses during the cooling process is strongly dependent on the initial fluid temperature T_{f_0} and the rate of temperature change ν_T. Figure 22 presents temperature distribution on the SGV surface at the time t = 500 s.

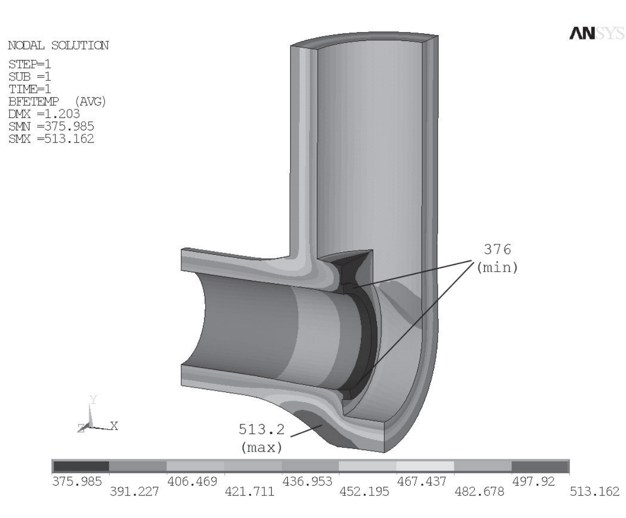

Fig. 22. Temperature distribution in °C during cooling operation after t = 500 s according to optimization method

The highest stress regions are located on the inner surface of the element (Fig. 23).

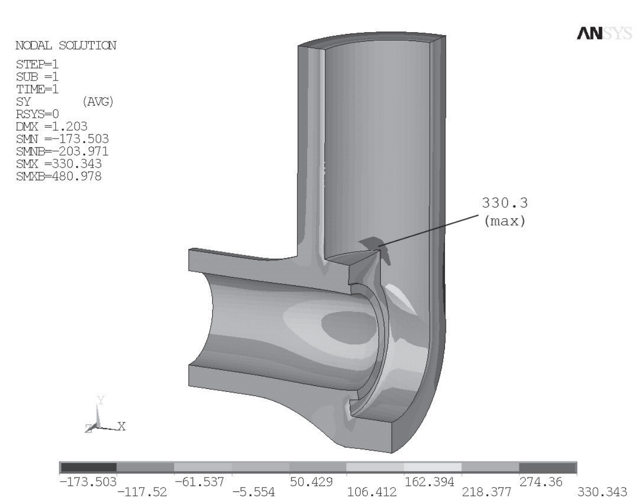

Fig. 23. Thermal stress σ_y distribution in MPa for $t = 500$ s during cooling operation

6. CONCLUSION

The thermal-strengths analysis revealed that high thermal stresses are formed during heating and cooling operations of the steam gate valve. During start-up phase, based on the German boiler regulations, thermal stresses go over the stress limit σ_a. In the case of shut-down phase they are kept far below the allowable stresses σ_a, but the operation is extended in time.

This paper presented the new numerical method that allows to estimate optimum heating and cooling parameters based on the thermal stress limitation. It was shown that optimum parameters allows to minimize start-up and shut-down operation time while keeping the maximum stresses within permitted limit. Presented method will be used in algorithm where thermal stresses in the construction are limited to allowable value. The new method is of great practical significance and can be implemented in the industry, wherever the heating and cooling processes take place. The optimum working parameters extend the longevity of the components, ipso facto, allows to operate in a cost-effective way. Safety regulations on power block devices are obeyed by conforming with TRD 301 code.

Acknowledgments

The authors would like to acknowledge the financial support of Ministry of Science and Higher Education in Poland. The investigations presented in the current paper have been partially supported by the research project No PBZ-MEiN-4/2/2006.

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