archives
of thermodynamics
Vol. **34**(2013), No. 3, 3–14
DOI: 10.2478/aoter-2013-0012

Determination of allowable fluid temperature during start-up operation of outlet header under the assumption of constant and temperature-dependent material properties

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Abstract Modern supercritical power plants operate at very high temperatures and pressures. Thus the construction elements are subjected to both high thermal and mechanical loads. As a result high stresses in those components are created. In order to operate safely, it is important to monitor stresses, especially during start-up and shut-down processes. The maximum stresses in the construction elements should not exceed the allowable stresses that are defined according to boiler regulations. It is important to find optimum operating parameters, that can assure safe heating and cooling processes. The optimum parameters define temperature and pressure histories that can keep the highest stresses within allowable limit and reduce operation time as much as possible. In this paper a new numerical method for determining optimum working fluid parameters is presented. In this method, properties of steel can be assumed as constant or temperature dependent. The constant value is taken usually at the average temperature of the operation cycle. For both cases optimal parameters are determined. Based on these parameters start-up operations for both cases are conducted. During entire processes stresses in the heated element are monitored. The results obtained are compared with German boiler regulations – Technische Regeln für Dampfkessel 301.

Keywords: Optimization methods; Total stresses; Steam boilers; Heat transfer

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Nomenclature

g – function of constrains
k – thermal conductivity, W/(mK)
p_w – working pressure of medium, MPa
S – the objective function
t – time, s
T_{f0} – initial temperature of medium, °C
T_w – working temperature of steam, °C
$\mathbf{x}$ – vector of searched parameters
$\mathbf{x}_l$ – vector containing the lower bounds of searched parameters
$\mathbf{x}_u$ – vector containing the upper bounds of searched parameters
v_T – rate of medium temperature change, K/min

Greek symbols

ε – convergence criterion
σ_a – allowable stresses, MPa
$\breve{\sigma}_i$ – allowable stresses during start-up (TRD), MPa
$\sigma_x, \sigma_y, \sigma_z$ – stresses in respective direction, MPa

1 Introduction

Start-up and shut-down operations of power blocks generate very high stresses in the construction elements. Theses stresses originate from high internal pressure and temperature of working medium [7]. Therefore, it is important to conduct these operations in such way that the total stresses do not exceed allowable stress limit, specified by boiler regulations. Thus start-up and shut-down operations must comply with strict regulations. Using German boiler regulations – Technische Regeln für Dampfkessel 301 (TRD 301) [8] – it is possible to calculate allowable stresses, σ_a, and working medium temperature change rates, v_{T_1}, and v_{T_2}. The calculation of theses parameters is based on the quasi-steady state and one dimensional temperature distribution assumption in the entire component. However, the quasi-steady state does not occur, especially at the beginning of the heating and cooling operations. Thus, the operations conducted with parameters estimated according to TRD 301 may cause stresses that exceed allowable stress limit.

Methods to find optimum operating parameters, that can assure safe heating and cooling processes can be found in [1-5]. Paper [3] presents the two-stage numerical method for determining optimum medium temperature transients under the assumption of constant material properties. This method ensures that the thermal stresses in the whole construction element does not exceed the allowable value. Firstly, change rate of medium temperature, based on the golden search method, is calculated. Next, the initial temperature step, utilizing Levenberg-Marquardt formula is found. Paper [4] presents numerical optimization procedure, based on Levenberg-Marquardt algorithm that allows to find change rate of medium temperature and initial temperature step, simultaneously. This procedure is based on the assumption that the total stresses in the entire construction elements do not exceed the allowable stresses. However, the assumption of constant material properties is valid.

This work presents new numerical method for determining optimum medium temperature transients, based on the assumption that the total stresses in the power block devices are kept within stress limit and material properties are constant or temperature-dependent. Implementation of the proposed method is presented for heating operations of outlet header. This construction element is mounted in supercritical power plants.

Outlet header is mounted in the power units of 460 MW and is designed for pressure $p_w = 29$ MPa and steam temperature $T_w = 559$ °C. The simplified model is presented in Fig. 1.

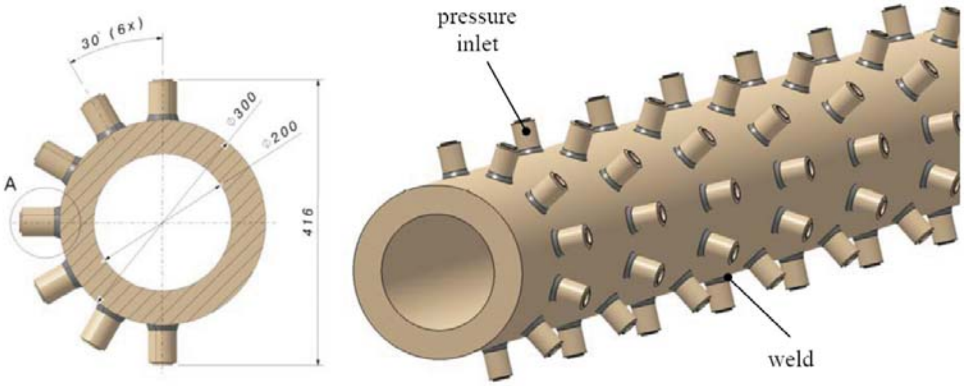

Figure 1. Geometry of outlet header in mm.

This thick-walled element is made of ferritic alloy steel X10Cr MoVNb9-1 (P91). The steel P91 is commonly used in the construction of supercritical power plants. It can withstand high temperatures and pressures for extended periods of time without significant weakening. Selected thermal and mechanical properties [9] are presented in Figs. 2 and 3.

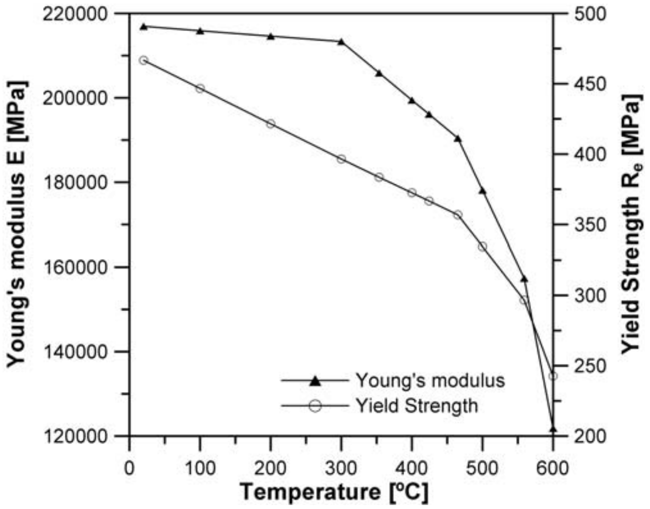

Figure 2. Mechanical properties of X10CrMoVNb9-1 (P91) steel.

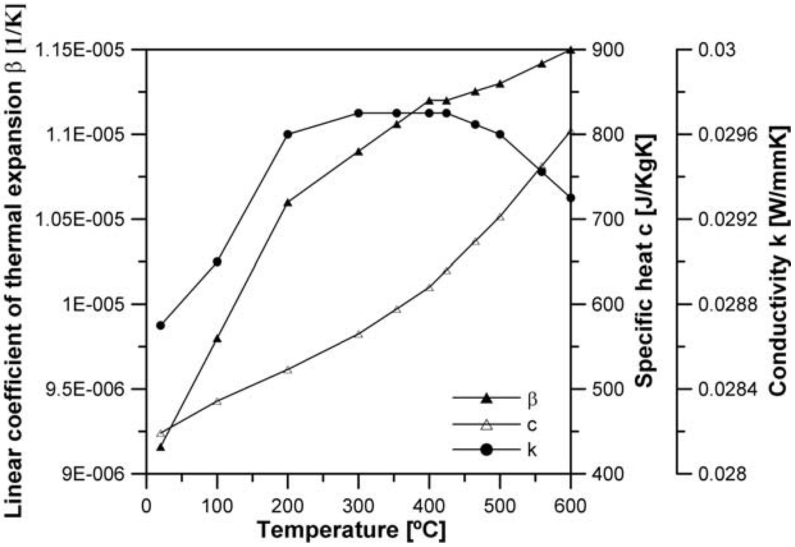

Figure 3. Thermal properties of X10CrMoVNb9-1 (P91) steel.

2 Formulation of the method

The presented optimization algorithm NLPQL (nonlinear programming by quadratic Lagrangian) for finding time-optimum temperature history uses a successive quadratic programming method to solve the general nonlinear programming problem [6,10,11]. A nonlinear optimization problem with inequality constraints is considered. The goal is to find a design vector $\mathbf{x}$ which minimizes the objective function defined as a total time of start-up operation

$$S\left(\mathbf{x}\right) = t_{tot} \tag{1}$$

subject to

$$g\left(\mathbf{x}\right) = \sigma_{\max_i}\left(\mathbf{x}\right) - \check{\sigma}_i \geq 0, \quad i = 1, 2,\ ..., n = \frac{t_{tot}}{\Delta t}\ , \tag{2}$$

$$\mathbf{x}_l \leq \mathbf{x} \leq \mathbf{x}_u\ , \tag{3}$$

where g is the function of constrains, t_{tot} and Δt denote the total time of start-up operation and time step, respectively, $\sigma_{\max_i}$ is the highest value of the compressive stresses component at time $t_i = t_0 + i\Delta t$ during the heating process, $\check{\sigma}_i$ denotes maximum allowable stress value according to TRD regulations and subscripts l and n denote lower and upper bounds of searched parameters, respectively. Considered restrictions apply compressive stresses, because they limit the speed of the heating process. The unknown parameters of $\mathbf{x}$ are denoted as $x_1 = T_{f_1}$, $x_2 = v_{T_1}$, $x_3 = T_{f_2}$, $x_4 = v_{T_2}$. The updating of the unknown parameters at every kth iteration step is performed based on the following rule

$$\mathbf{x}^{(k+1)} = \mathbf{x}^{(k)} + \lambda\mathbf{s}^{(k)}\ , \tag{4}$$

where $\mathbf{x}^{(k)}$ is the current iterate, and superscript (k) denotes current iteration, λ is the optimal step length along the direction $\mathbf{s}$. The method obtains subproblems by using a quadratic approximation of the Lagrangian and by linearizing the constraints. Thus, the subproblem can be formulated as follows [6,10,11]. Find vector $\mathbf{s}$ which minimizes function $q(\mathbf{s})$

$$q\left(\mathbf{s}\right) = \nabla S\left(\mathbf{x}^{(k)}\right)^T \mathbf{s} + \frac{1}{2}\mathbf{s}^T\mathbf{H}\mathbf{s} \tag{5}$$

with restrictions

$$g_j\left(\mathbf{x}\right) + \nabla g_j\left(\mathbf{x}\right)^T \mathbf{s} \geq 0, \quad j = 1,\ 2,\ ...,\ m\ , \tag{6}$$

$$\mathbf{x}_l - \mathbf{x}_k \leq \mathbf{s} \leq \mathbf{x}_u - \mathbf{x}_k\ , \tag{7}$$

where $\mathbf{H}$ is a positive definite approximation of the Hessian, m is the number of constrains and superscript T denotes the transpose.

3 Application of optimization method

In this section, application of optimization method for finding optimum temperature history during cold start-up of outlet header is presented. The optimum temperature should assure that the heating operation is conducted in the shortest time and the total stresses in the construction element do not exceed the allowable stress $\breve{\sigma}_i$. It is assumed that optimum temperature is described by four parameters T_{f_1}, v_{T_1}, T_{f_2}, v_{T_2}, where T_{f_1}, T_{f_2} are step changes of temperature and v_{T_1}, v_{T_2} denote temperature change rates (Fig. 4).

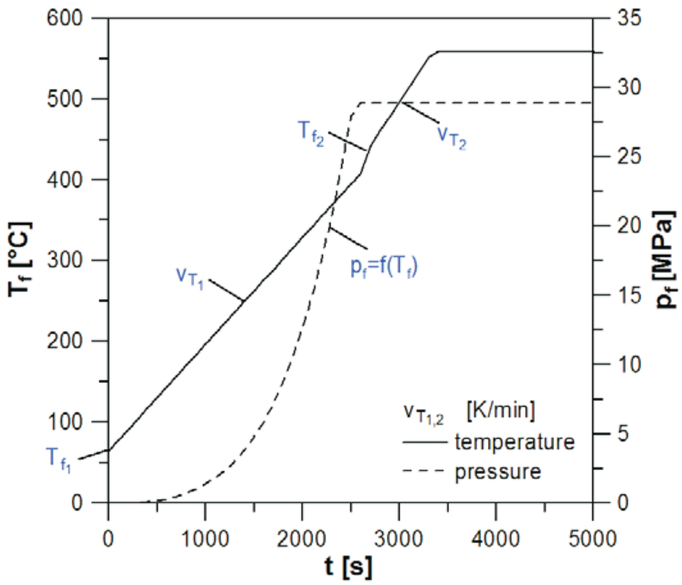

Figure 4. Optimum working medium temperature and pressure histories.

Working medium pressure, p_f, changes as a function of temperature in accordance with saturation curve

$$p_f = \left(\frac{T_f - a}{b} \right)^{\frac{1}{c}}, \tag{8}$$

where: $a = -25.72743$, $b = 205.38723$, $c = 0.2150989$.

In order to simulate start-up operation and monitor maximum stresses in the heated element finite element method (FEM) program was used [12]. The outlet header geometry was divided into eight-node finite elements.

Since the element is symmetrical only one half was modeled and analyzed as shown in Fig. 5.

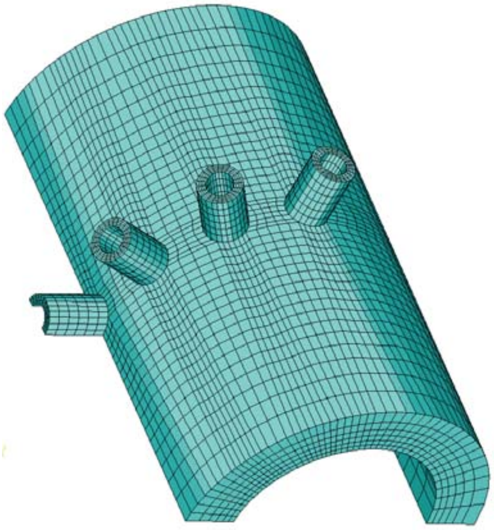

Figure 5. The outlet header divided into finite elements.

In calculations both constant and temperature-dependent steel properties were used. The constant steel properties were estimated at calculation temperature 424.4 °C according to TRD regulations: Young modulus – 196112 MPa, thermal expansion coefficient – 1.12^{-5} 1/K, specific heat – 640.1 J/(kg K), thermal conductivity – 29.7 W/(m K), density – 7750 kg/m^3, Poisson's ratio – 0.3. The temperature-dependent steel properties used in the simulation were shown in Figs. 2 and 3. On the heated surface constant heat transfer coefficient $\alpha = 2000$ W/(m^2K) according to PN-EN 12952-3 was assumed. The outer surface was perfectly isolated, so there was no heat exchange between the heated component and the surrounding environment. Using the NLPQL optimization method four parameters defining the time-optimum temperature for constant and variable material properties were found.

The complete temperature and pressure history is shown in Fig. 6. The maximum total stresses monitored during the entire heating processes described in Tab. 1 are shown in Fig. 7. The results presented in Fig. 7 indicate that the heating operations conducted with optimum parameters for both cases can limit maximum stresses in the components to the allowable

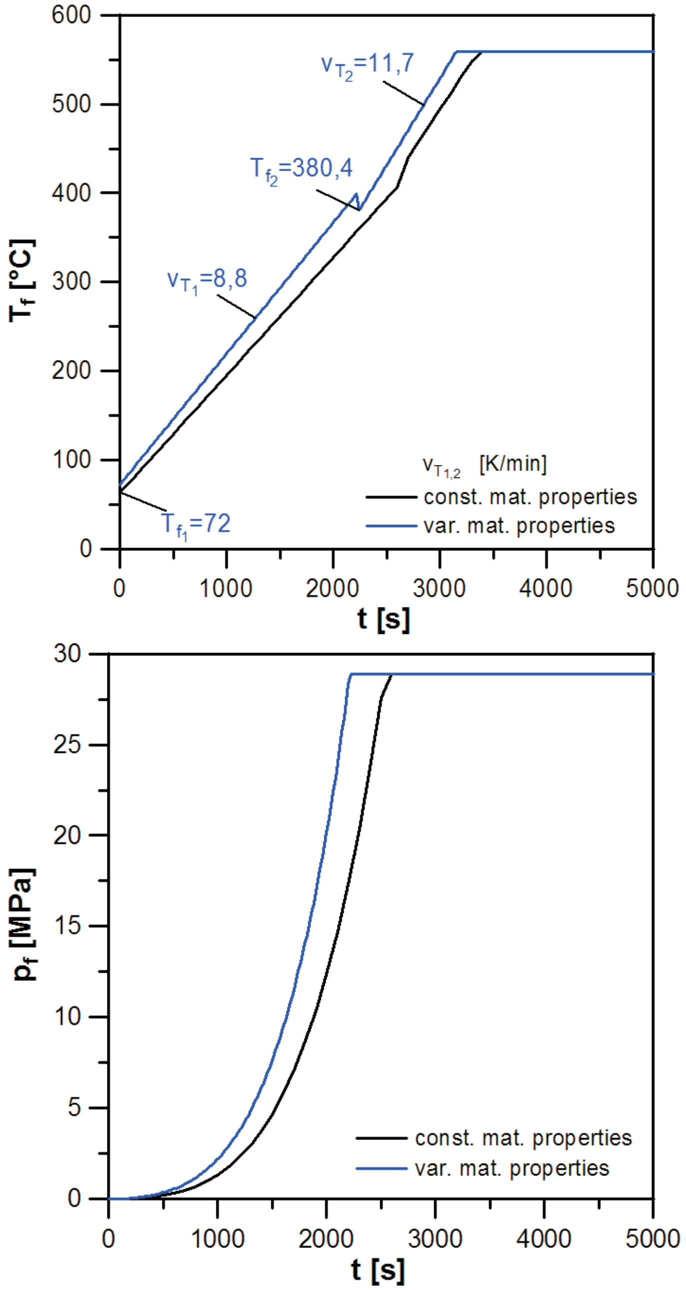

Figure 6. Optimum working medium temperature and pressure histories found based on NLPQL method.

Table 1. Calculated parameters assuming constant and temperature-dependent material properties.

P91 material properties	Allowable stress	First step temperature change	First temperature change rate	Second step temperature change	Second temperature change rate
	$\breve{\sigma}_i$ [MPa]	T_{f_1} [°C]	v_{T_1} [K/min]	T_{f_2} [°C]	v_{T_2} [K/min]
Constant	−126.7	62.95	7.94	439.95	10.9
Temperature-dependent	−126.7	72.00	8.80	380.40	11.7

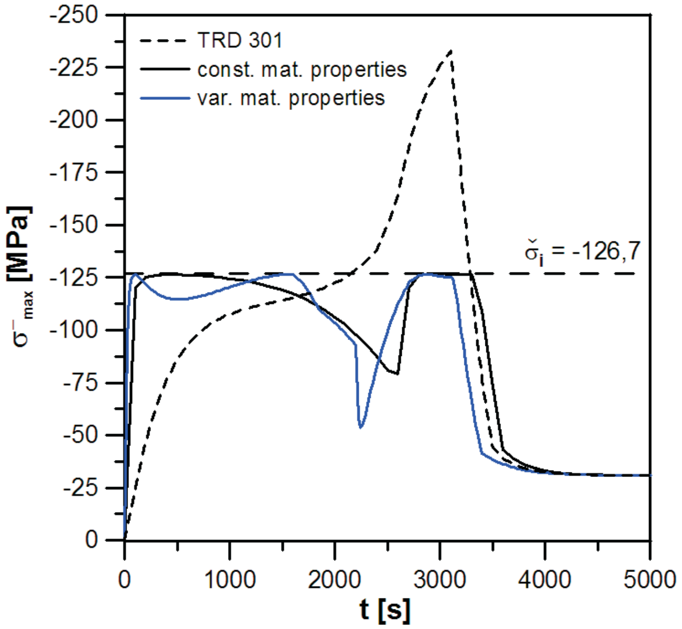

Figure 7. Maximum compressive stress history during heating operation according to TRD regulations and optimization method using constant and variable steel properties.

stresses. The highest compressive stresses were observed at time $t = 2860$ s at the opening edges on the inner surface as plotted in Fig. 8. Figure 9 shows maximum tensile stress areas located on the outer surface with the highest value of 142.48 MPa.

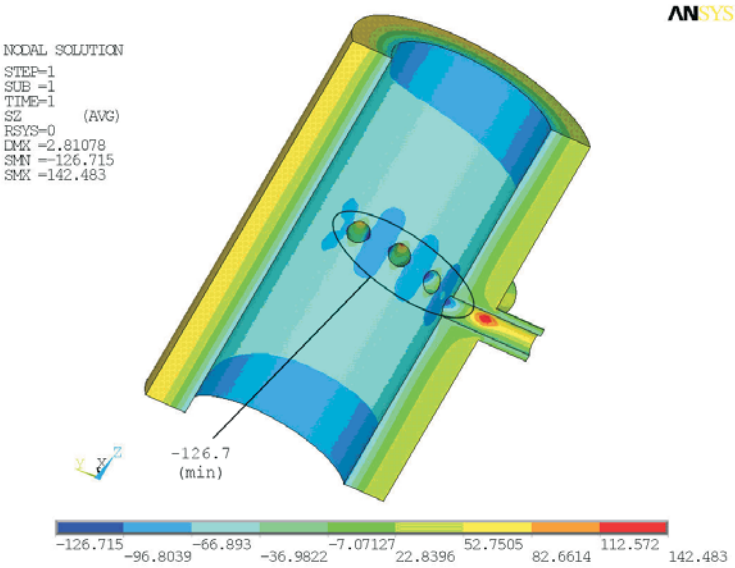

Figure 8. Compressive stress σ_z distribution on the inner surface in MPa for $t = 2860$ s.

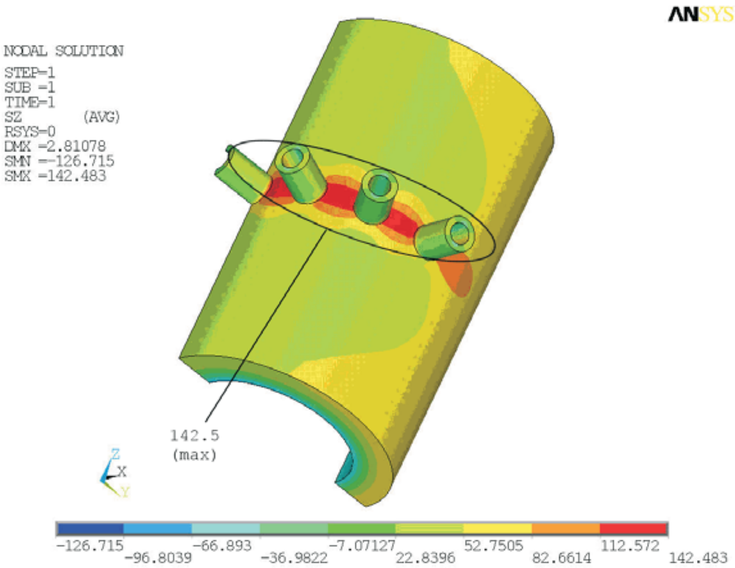

Figure 9. Tensile stress σ_z distribution on the outer surface in MPa for $t = 2860$ s.

4 Conclusions

In this paper numerical simulation of cold start-up operation of outlet header was presented. The start-up operation was conducted with the use of a general nonlinear programming algorithm NLPQL implemented by Schittkowski [6]. Using this algorithm optimum cold start-up parameters were found. Both constant and temperature-dependent steel properties were considered in the analysis. The results show that the heating operations conducted with optimum parameters for both cases can limit maximum stresses in the components to the allowable stresses. However, it is useful to consider temperature-dependent steel properties because the time of start-up operation can be reduced.

Acknowledgement This work was partially supported by scientific project no. NR15-0060-10/2011. Part of this work was done within the confines of cooperation between TÜV NORD EnSys Hannover GmbH & Co. KG and Cracow University of Technology.

Received 8 July 2013

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