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Bartosz Kraszewski ✉; Grzegorz Bzymek; Paweł Ziółkowski; Janusz Badur

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Extremal Thermal Loading of a Bifurcation Pipe

Bartosz Kraszewski[1, a)], Grzegorz Bzymek[2, b)], Paweł Ziółkowski[3, c)] and Janusz Badur[1, d)]

[1] *Institute of Fluid-Flow Machinery Polish Academy of Sciences, Centre of Flow and Combustion, Energy Conversion Department*
Fiszera 14 st., 80-231 Gdańsk, Poland

[2] *PGE GiEK S. A. Opole Power Plant Branch, Poland*

[3] *Gdańsk University of Technology, Faculty of Mechanical Engineering, Department of Energy and Industrial Apparatus*
Narutowicza 11/12 st., 80-233 Gdańsk, Poland

[a)]Corresponding author: bkraszewski@imp.gda.pl
[b)] grzegorz.bzymek@gkpge.pl
[c)] pawel.ziolkowski@imp.gda.pl
[d)]janusz.badur@imp.gda.pl

Abstract. The subject of considerations is a spherical bifurcation pipe of a live steam made of steel P91, which is an element of a block of coal-fired power plant working with a 18K370 turbine. As experience shows, it is a very sensitive element of the boiler pipelines. An extreme work scenario for such a block has been adopted, in which the turbine is shutting down to a warm state three times in 24 hours. This is an action dictated by new challenges in the field of electricity network regulation, caused by increasing share of renewable energy sources. A one-sided numerical thermal-FSI analysis was performed. The focus was on hoop stresses as the most significant for the bifurcation pipe durability. The daily runs of these stresses at three points of the thickness of the bifurcation pipe sphere have been presented. Mechanical stresses derived from pressure and thermal stresses derived from temperature changes have been isolated. It has been shown that depending on the thermal load, some areas of the cross section are compressed while adjacent ones are stretched and vice versa. Thus, the mechanical stresses can be reduced under thermal conditions by thermal stresses. It has been proven that the bifurcation pipe is able to withstand the given extreme loads with stresses more than twice smaller than the yield point at a given operating temperature.

INTRODUCTION

As it is commonly known, the share of renewable energy sources growing each year, despite the favorable influence of the natural environment, causes problems in the regulation of the power grid. This is because the volatility of weather conditions, and it is intensified by priority in receiving energy from these sources. In order to meet the stability of the grid, it is necessary to redefine the working methods of the currently existing steam power units. A significant part of them is not adapted to fast load changes or quick starts and shutdowns. Adaptation of such a block to modern requirements brings with it its thorough retrofitting. There is also another option - the use of modern, more accurate measuring and numerical tools to precisely determine the strength aspects of the boiler-turbine system. It may turn out that due to the inaccuracy of the old calculation methods, a given element has been designed with a high strength allowance and can work in new, harder conditions without retrofitting. One of such tools is the numerical

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model of thermal Fluid-Structure Interaction, consisting of Computational Fluid Dynamics (CFD) and Computational Solid Dynamics (CSD). It allows for relatively accurate prediction of the effects of steam on steel structures.

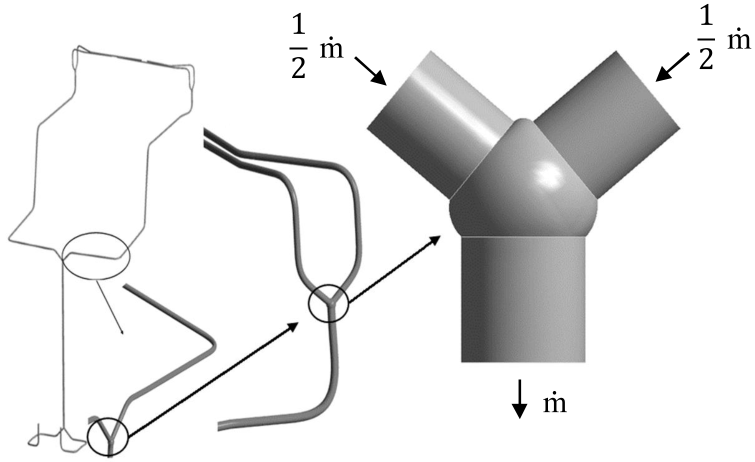


FIGURE 1. Placement and the highlight of the bifurcation pipe.

The article is devoted to the thermal-FSI analysis of one of the critical elements of the boiler-turbine system, which is a live steam bifurcation pipe. It is an element of the power plant block working with the 18K370 turbine, located in the upper part of the boiler outlet, as shown in Fig. 1. The bifurcation pipe has the task of combining two steam streams into one, and as experience shows, it is quite a sensitive device. The material from which this element is made is steel P91, well known in the power engineering sector. This work assumes that the power plant block, and thus the bifurcation pipe, is shutting down three times in a day. This is an unprecedented action, resulting in high thermal stresses, which can be termed the concept of extreme work.

The term thermal-FSI in the field of durability of power engineering installations has been developed for many years in the Department of Energy Conversion of the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences (IFFM PAS) [1, 2, 3, 4, 5] including considerations regarding the use of the Burzyński strength hypothesis [6, 7] and the Navier-Stokes slip layer concept [8, 9, 10]. The works of M. Banaszkiewicz [11, 12, 13] in the field of power engineering installations damage are also worth attention.

Heat exchange and equivalent stress issues in the form of elastic-plastic adaptation of the same live steam bifurcation pipe were addressed by D. Sławiński [14, 15]. The author proves that it is possible to conduct startups faster than the manufacturer's recommendations, while maintaining the elastic nature of the deformations. Then, in the paper [16], the authors, using the example of a spherical valve, note that a better solution in terms of durability is the separate monitoring of axial and hoop stresses, rather than reduced stresses. This fact coincides with the IFFM PAS's own experience, according to which the destruction of pipeline elements at high temperatures often occurs according to hoop stresses. This is due to the relatively low value of radial stresses and the method of hanging piping, reducing axial stresses. Therefore, only hoop stresses will be considered in this work.

ASSUMPTIONS OF NUMERICAL ANALYSIS

Mathematical Model

Assuming the situation in which the fluid comes into contact with a solid body, there can be defined the contact surface Ω_{FSI}, its speed of movement $\mathbf{w}_{\Omega}$, instantaneous volumes of liquid and solid ∂V_F, ∂V_S and also vectors normal to the surfaces $\mathbf{n}_F$, $\mathbf{n}_S$ [5, 8, 14], as shown in Fig. 2. Considering that the flow of fluxes $\mathcal{F}$ within a fluid-solid interaction must be preserved, the following relationship must be met [14, 17]:

$$\mathcal{F}_F = \mathcal{F}_S . \tag{1}$$

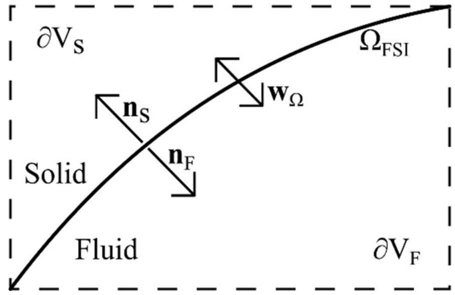


FIGURE 2. Theoretical fluid-solid mid-surface.

Referring to the above dependence, there can be defined three following FSI balance equations:

- transfer of mass flux;

$$\mathbf{j}\mathbf{n}_F = \mathbf{j}\mathbf{n}_S\,, \qquad \mathbf{j} = \sum \rho_i \mathbf{v}_\mathrm{i}\,, \tag{2}$$

- transfer of momentum flux;

$$\left(-p\mathbf{I} + \boldsymbol{\tau}^{(m)}\right) \cdot \mathbf{n}_F = \boldsymbol{\sigma}\mathbf{n}_S + \mathcal{M}_\Omega\,, \tag{3}$$

- transfer of energy flux;

$$\left(-p\mathbf{v}_F + \boldsymbol{\tau}^{(m)}\mathbf{v}_F + \mathbf{q}_F\right) \cdot \mathbf{n}_F = (\boldsymbol{\sigma}\mathbf{v}_S + \mathbf{q}_S) \cdot \mathbf{n}_S + e_\Omega\,, \tag{4}$$

In the above equations ρ is a density of the continuum, $\mathbf{v}$ ($\mathbf{x}$, t) is the velocity vector, p is the hydrostatic pressure, $\mathbf{I}$ is an unit tensor, $\boldsymbol{\sigma}$ is the stresses tensor of solid body and $\boldsymbol{\tau}^{(m)}$ stands for the molecular tensor of total viscous stresses. Additionally, $\mathcal{M}_\Omega$ has been taken into account as a surface tension flux and e_Ω as a surface tension energy. The conservative equations can also be prepared separately for each continuum [4, 6, 18, 17] - as well as heat fluxes. The quantity and accuracy of heat exchange description depend on these two equations:

$$\mathbf{q}_F = \mathbf{q}_F^{(l)} + \mathbf{q}_F^{(t)} + \mathbf{q}_F^{(r)} + \cdots \tag{5}$$

$$\mathbf{q}_S = \mathbf{q}_S^{(m)} + \mathbf{q}_S^{(t)} + \mathbf{q}_S^{(r)} + \cdots. \tag{6}$$

The index (l) refers to the laminar heat flux, (t) to the turbulent heat flux dependent on the fluctuation of the temperature field, (r) refers to the radiant heat transfer, and index (m) means the molecular heat exchange.

To analyze the hoop stresses, a cylindrical coordinate system with axial a, radial r and circumferential θ directions was assumed, in which the main axis coincides with the axis of the outlet pipeline. Stress tensor in this system can be written as:

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{rr} & \tau_{r\theta} & \tau_{ra} \\ \tau_{\theta x} & \sigma_{\theta\theta} & \tau_{\theta a} \\ \tau_{ar} & \tau_{a\theta} & \sigma_{aa} \end{bmatrix} \tag{7}$$

where σ refers to the main stresses, and τ refers to the shear stresses.

Boundary Conditions

In order to conduct a numerical analysis of the Computational Fluid Dynamics, a 24-hour scenario of the extreme operation of the power plant block was assumed, based on the real operational parameters of the 18K370 turbine. In the runs visible in FIG. 3, an unprecedented 1-hour start-up and shutdown procedure was adopted. It was assumed that after 6 hours of warm state (300°C, 20 bar), the block reaches the maximum power of 400 MW, steam mass flow of 296 kg/s, pressure of 200 bar and the temperature of 590°C (at the boiler outlet) in the morning peak, after which it is shutting down to a warm state for 2 hours. Subsequently, the start-up is set to 360 MW, 266 kg/s, 180 bar and 590°C for a period of 1 hour at the noon peak. After the next 2 hours-long shutdown, the block is started-up to the full power in the evening peak for 3 hours, to be put into a night valley at 10 p.m. It should be noted that in a given system the full boiler steam stream flows through the analyzed bifurcation pipe.

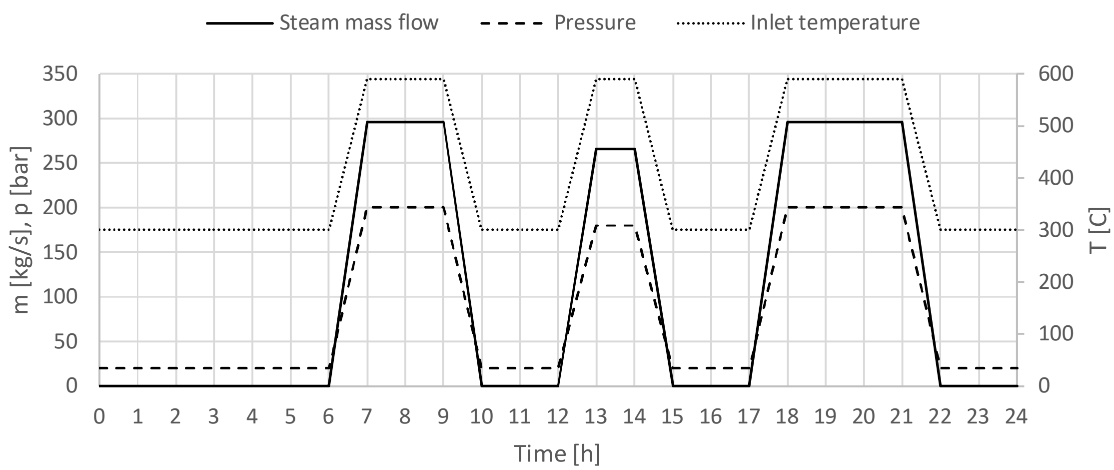
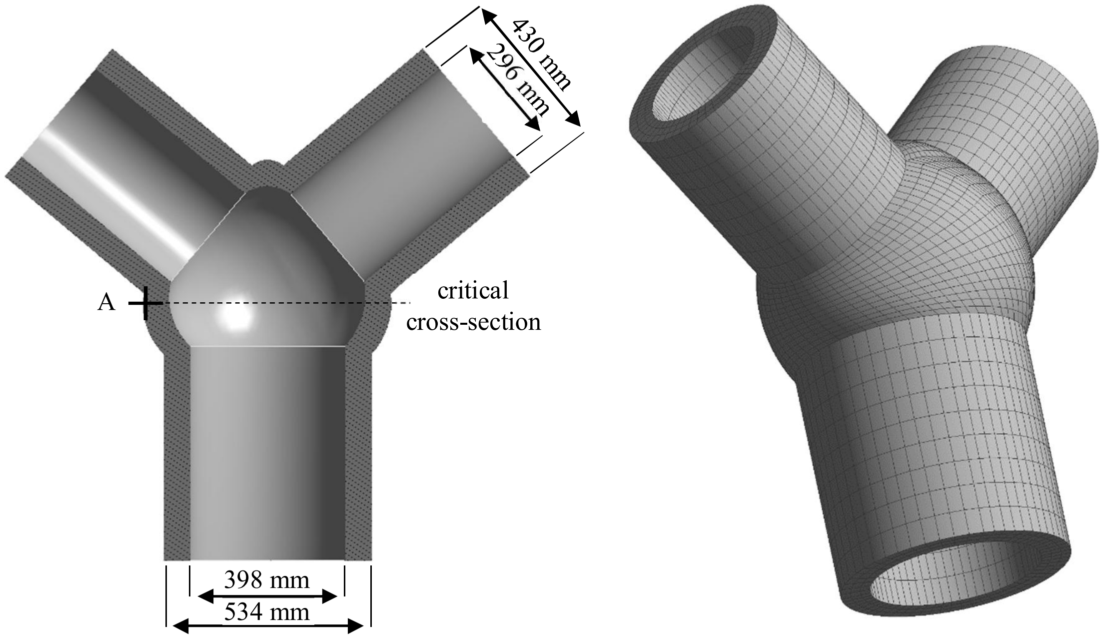


FIGURE 3. Daily runs of the parameters in the extreme thermal load scenario.

The numerical analysis of Thermal-FSI was carried out in a quasi-static condition. The CFD simulation was in a fully non-stationary form, providing pressure and temperature fields. Next, the characteristic states of the simulation were selected and Computational Structure Dynamic (CSD) analysis in a stationary form. Support of the bifurcation pipe model for CSD purposes took into account its stabilization by the outlet pipeline as well as freedom of movement (deformation) through its hanging mounting method.

Geometry and Discretization

The three-dimensional bifurcation pipe model used in the numerical analysis is shown in Fig. 4a. For each of the two inlet pipelines with an inner diameter of 296 mm and a wall thickness of 67 mm, half of the current steam stream was fed. Both supplied streams mix in the bifurcation pipe sphere and are led out through a discharge pipe with an internal diameter of 398 mm and a wall thickness of 86 mm. The critical cross-section of the geometry in which the greatest wall stress is predicted is set at the full diameter of the sphere, under the inlets. The geometry of the bifurcation pipe was discretized with a structured grid visible in Fig. 4b, obtaining 9585 elements and 13136 nodes.



(a) (b)

FIGURE 4. Geometry (a) and discretization grid (b) of the analyzed bifurcation pipe.

The steam properties have been read from the steam tables for the characteristic load points and then linearized. The properties of P91 steel were also linearized based on the data presented in the TAB. 1 [19]. The density of steel P91 was assumed to be constant in a given temperature range, equal to $7.76 \cdot 10^9$ kg/m^3.

TABLE 1. Parameters of P91 steel [19].

Temperature [°C]	**Young's modulus [10^3 MPa]**	**0% yield point [MPa]**	**0.35% yield point [MPa]**	**Coefficient of thermal conductivity [W/(mK)]**	**Coefficient of thermal expansion [10^5 1/K]**
300	200	420	630	29.7	1.09
400	186	398	597	29.7	1.12
500	172	372	558	29.6	1.13
600	158	261	391	29.3	1.15

RESULTS

After the numerical CFD simulation of the live steam bifurcation pipe, corresponding to the daily, extreme operation of the power plant unit, temperature distributions were obtained in its volume. Fig. 5 shows the diurnal temperature of the steam flowing through the bifurcation pipe and the temperature at the point "A" lying on the external surface of the bifurcation pipe in the critical cross-section line. The graph shows the periods of the largest differences in temperature between the medium and the external, suggesting the time points of the occurrence of the greatest thermal stresses. The largest temperature differences occurred with the ends of the loading and the ends of the unloading of the power plant unit. For example, this difference in the 7th hour of the scenario, after the end of the load increase, was 47°C, and in 10th hour of the scenario, after the unloading amounts 58°C. The temperature distributions in the longitudinal cross-section of the bifurcation pipe for both cases are shown in Fig. 6

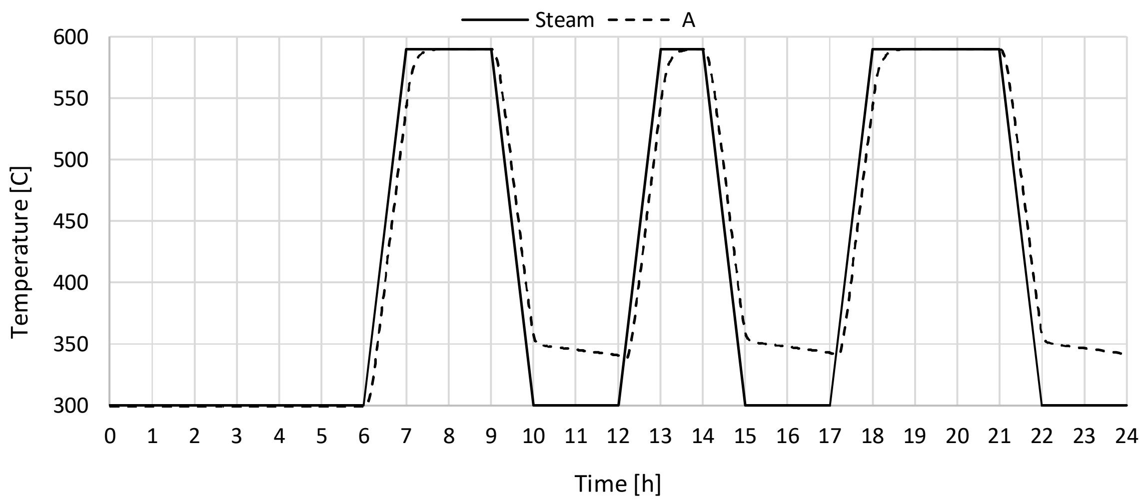
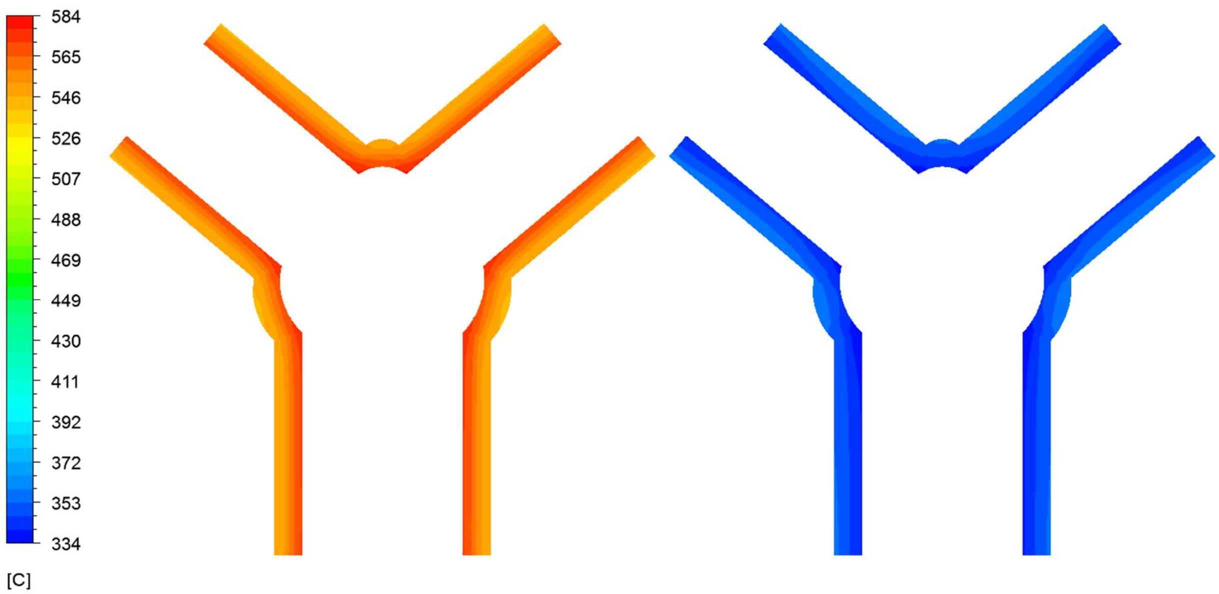


FIGURE 5. Steam temperature and temperature at the "A" point in the given work scenario.



(a) (b)

FIGURE 6. Temperature distributions in the longitudinal cross-sections of the bifurcation pipe; (a) 7th hour of the work scenario, (b) 10th hour of the work scenario.

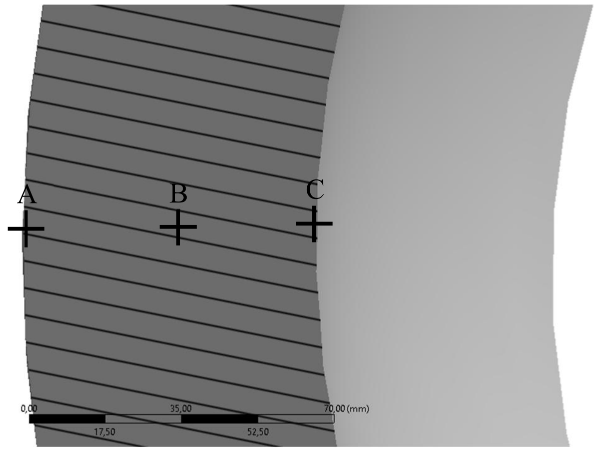
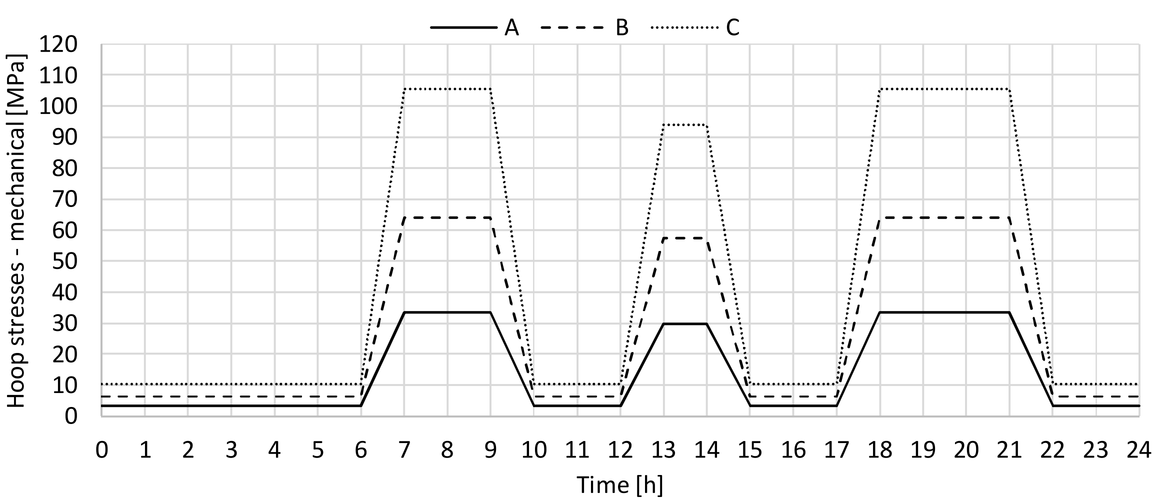


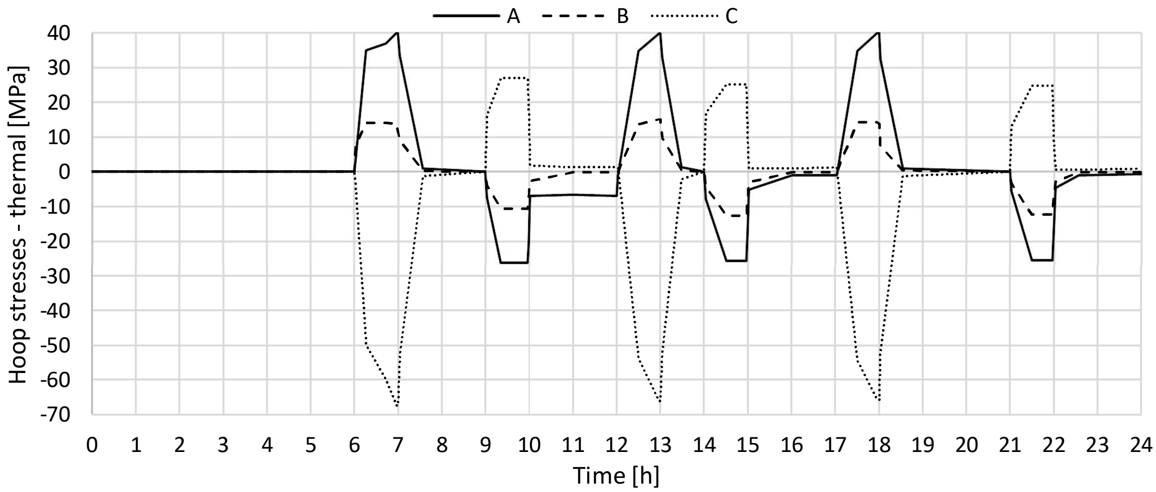
FIGURE 7. The top view of the wall within the critical cross-section with designated points.

Then, on the basis of the obtained temperature distributions and the given pressure in the selected time steps, a static CSD analysis was made. In the critical cross-section, 3 points along the wall thickness were determined - point "A" located on the outer surface, "B" located in the middle of the wall thickness and point "C" lying on the inner surface, as shown in Fig. 7. For each of these points, mechanical, thermal and total diurnal hoop stresses were determined. Positive values of these stresses refer to the material's stretching, and negative to its compression. The mechanical hoop stresses resulting from the influence of the steam pressure on the bifurcation pipe's walls are shown in Fig. 8a. The thermal hoop stresses resulting from temperature differences along the wall thickness are presented in Fig. 8b. Fig. 8c shows the summed-up hoop stresses.

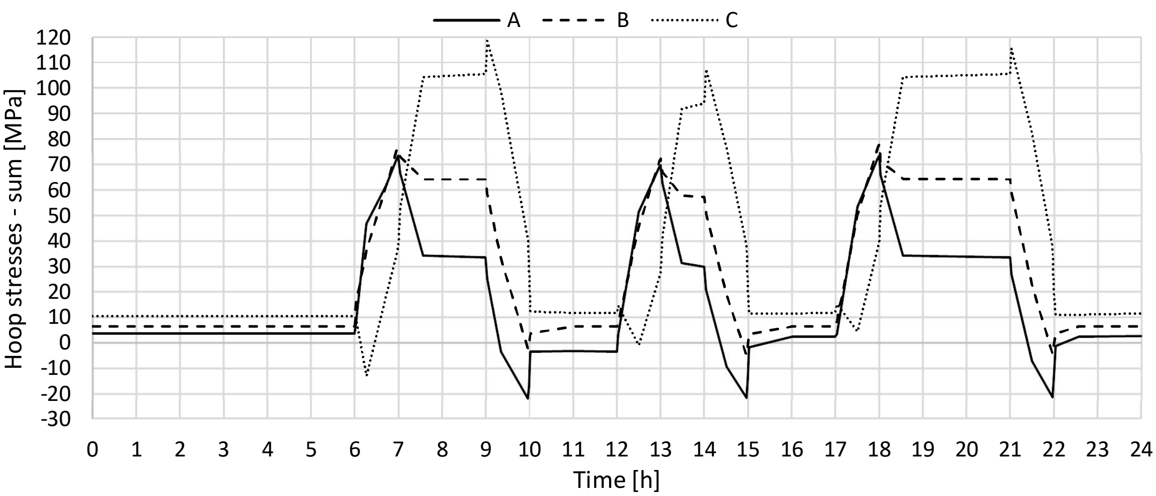
In a given extreme load scenario, the total hoop stresses of the bifurcation pipe for individual peaks of the network load were getting smaller (slightly). This was caused by the heating up of the element and smaller temperature differences. The plasticity limit of P91 steel, amounting 261 MPa at 600°C, has not been exceeded, keeping more than two times the reserve. Thus, the results of Thermal-FSI numerical analysis suggest that the bifurcation pipe will withstand the given extreme work scenario. However, it should be borne in mind that it is only one link in the chain of the steam power plant unit.



(a)



(b)



(c)

FIGURE 8. Comparison of hoop stresses in points B, C, D: (a) mechanical, (b) thermal, (c) total.

CONCLUSIONS

First of all, numerical analysis of the CFD start-up and the daily work of the bifurcation pipe of the power plant unit allowed to obtain temperature distributions in its wall thickness. As shown in Fig. 5, the largest temperature differences between the pair and the outer wall occurred with the end of the unloading.

Then a stationary numerical analysis of CSD was performed, based on the given pressure and temperature distributions at selected time points. The pressure effects presented in Fig. 8a show a linear relationship between the steam pressure and the tensile hoop stresses of up to 106 MPa for the "C" point located on the inside wall.

The analysis of thermal hoop stresses showed a much larger variation, characterized by a non-linear response of stresses to the given temperature, as shown in Fig. 8b. The largest values of hoop stresses were noted at the moment of ending the load on the power plant unit. On the example of the 7th hour of the load scenario, it can be noticed that while the external point "A" is stretched by a stress of 40 MPa, at the same time the point "B" is compressed under tension of 68 MPa. The situation during cooling is reversed: the "A" point is compressed by a stress of 26 MPa, and the "C" point is stretched by stress of 27 MPa. The "B" point for both cases reached small values of hoop stresses, assuming the nature of stresses in line with those in "A". This means that the transition border from one stress character to another lies between points "B" and "C".

The summed mechanical and thermal hoop stresses, shown in Fig. 8c, reach the highest stretching value of 119 MPa, along with the beginning of load reduction. Bearing in mind the opposing character of stresses at certain time points, attention should be paid to the stresses reduction taking place - for example, for the 7th hour of the scenario at point "C", thermal compressive stresses are reducing mechanical stretching stresses.

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