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Thermal-FSI modeling of steam turbine accelerated start-up by means of cooling steam injection control

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Abstract

This paper presents the results of analysis of steam turbine start-up using Thermal-FSI (Thermal-Fluid-Structure-Interaction). Reference and acceleration start simulations were carried out. Attention focused on a steam unit as they account for most electricity generation in Poland. Accelerated start-up is of interest as a possible method for reducing the adverse impact of renewable energy by controlling the injection of cooling steam, set against the backdrop of increasing RES and their negative impact on the operation of steam units. The work is the result of research into the possibility of accelerating the start-up of a steam turbine.

Keywords: Thermal-FSI, unit elasticity, steam turbine, start-up

1 Introduction

The Polish energy sector has encountered problems related to the impact of renewable energy sources. Amid the media hype, there is a negative side to wind turbines and photovoltaics [1]; [2]. Current market conditions give priority in the production of electricity to power plants using RES. Within a few minutes, wind speed can increase dramatically, clearly translating into an increase in energy generated by wind turbines. In this situation, traditional generating units must reduce power to adapt to the requirements of the power grid. The reverse happens when the wind suddenly stops blowing. Then, electricity generation units must quickly increase their power output to cover the needs of the system. When talking about generating units, we primarily mean steam turbines working in plants with boilers fired with hard coal or lignite.

In the past, a rotating reserve would cover changes in load power within 10 minutes. If the load is expected to increase, installations must be ready to take up the load [3]; [4]. In addition, certain baseload plants would produce large amounts of electricity at low cost, due to the higher efficiency of installations with greater installed power [3]; [4]. This translates into clear unit fuel consumption, energy price and environmental aspects related to the production of energy. Evidently, fuel prices are of great importance here, as we know brown coal is cheaper than either hard coal or gas. Nevertheless, over time supercritical plants will have to reduce their power in order to help develop wind installations. Currently, out of concern for stable boiler operation and steam flow in the turbine, the load should not take values lower than 40% of the rated load [5]; [6]. The plants on which the digression is being done should be adjusted (to the extent possible) to the new conditions with regard to their minimum burden.

Whereas newer units are adapted to working with loads of 40%, older units were not designed for such parameters. Hence, wind turbines have a negative impact in terms of frequent start-ups and withdrawal of steam turbines. Returning to the peak load of the system, it should be noted that the peak load was taken by older turbines. In addition, they were specially designed for this purpose. Older units mean a simpler construction and a simpler control system.

Due to the increasing power of weather-dependent RES sources, large steam plants have to be kept in the hot reserve [1]. Steps that can be taken to fulfill this task by making the plant's work more flexible are described in [1]; [7]; [4]; [8]. The situation of controlling the system's power essentially involves more frequent starts and withdrawals of turbine sets, including high power ones. To this end, the start-up of the turbine set can be accelerated by considering the elastic-plastic adaptation of the structure, as described in [7]; [1], or through using cooling by intake vapor, or a working medium with lower parameters [9]; [10]; [11]; [4].

To address the problems faced by steam units, Thermal-FSI [12]; [13]; [14]; [15] analysis of the accelerated start-up of the steam turbine was carried out in order to determine the possibility of acceleration.

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2 Analyzed Geometry

Based on the actual geometry of the WP part of the 18K390 turbine from Bełchatów Power Plant Fig.1, two models were made which were subjected to Thermal-FSI analysis.

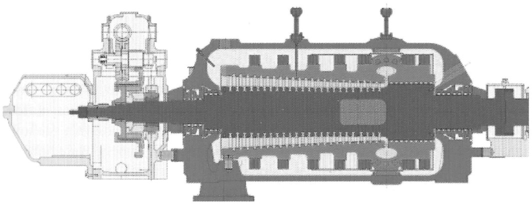

Figure 1: Cross section of the turbine's 18K390 HP part [4]

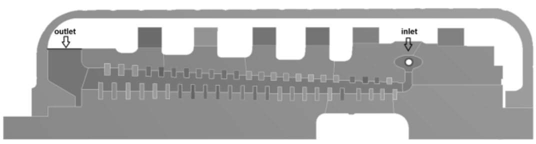

Figure 2: Reference model of the WP part of the 18K390 turbine with marked inlet and outlet edges

As can be seen in Fig. 2, the model being analyzed was simplified to meet the needs of the two-dimensional analysis.

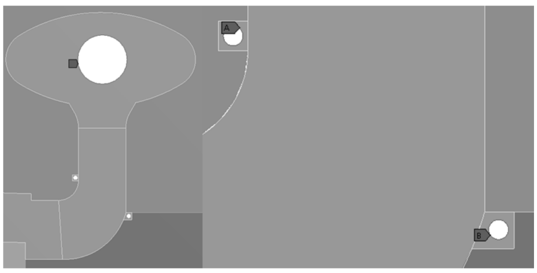

Figure 3: Close-up of the area of additional inlets

As the modified geometry differs only by two additional inlets, Fig.3 is shown. The additional cooling steam flow in the initial start-up phase can be taken from the units main line and in the next phase of the start-up from the high-pressure part of the boiler, where the saturation temperature at a given pressure is 300 .

3 Set of equations - CFD

In terms of solving the fluid problem, three basic equations of mass, momentum and energy conservation were solved, expanded by two evolution equations for parameters k and ε [16]; [13]; [4]; [15].

Conservation of mass equation (1):

$$\delta_t(\rho) + \text{div}(\rho \mathbf{v}) = 0 \tag{1}$$

Conservation of momentum equation(2):

$$\delta_t(\rho \mathbf{v}) + \text{div}(\rho \mathbf{v} \otimes \mathbf{v} + p\mathbf{I}) = \text{div}(\tau^c) + \rho \mathbf{b} \tag{2}$$

Conservation of energy equation (3):

$$\delta_t(\rho e) + \text{div}(\rho e \mathbf{v} + p \mathbf{v}) = \text{div}(\tau^c \mathbf{v} + \mathbf{q}^c) + \rho \mathbf{b} \mathbf{v} \tag{3}$$

Evolution equation concerning turbulent energy *k* (4):

$$\delta_t(\rho k) + \text{div}(\rho k \mathbf{v}) = \text{div}(\mathbf{J}_k) + S_k \tag{4}$$

Evolution equation concerning energy dissipation ε (5):

$$\delta_t(\rho e) + \text{div}(\rho e \mathbf{v}) = \text{div}(\mathbf{J}_e) + S_e \tag{5}$$

A more detailed description of the models used in CFD codes can also be found in [16].

4 Set of equations - CSD

CFD solver provides field of temperature, stress fields and strain fields. In the case of a solid body, we have the same three conservation equations (mass, momentum and energy) as described above. Our analysis and calculations in a solid body are based on the 3D analysis typical for the CSD [7]; [12]. CSD is a point-blank analogy of CFD (Computational Fluid Dynamics). The discretization method for CSD and CFD is arbitrary (FEM, FVM, etc.) but the governing equations are identical. This architecture of solving equations greatly simplifies Thermal-FSI analyses.

Thermal-FSI analysis consists in coupling with the help of the basic equation, in this case the energy equation (temperature) of the fluid domain with the domain of the solid. The resulting temperature fields from the flow analysis are exported to the solid state solver, and a strength analysis is performed based on them [12]; [13]; [14]; [4].

To simulate material effort related to stresses emerging in material, the following Huber-Mises-Hencky reduced tensions have been used [12]; [13]. Dividing the internal Energy into axial (volumetric) and deviation (formative) parts according to the relation (6):

$$\phi = \phi_v + \phi_f \leq K \tag{6}$$

and then, assuming that the volumetric part of the energy does not contribute to the concentration of the material but only to the change of volume, then condition (6) is reduced to form (7):

$$\phi_f \leq K \tag{7}$$

Resulting from this assumption reduced H-M-H stress is given by formula (8):

$$\sigma_{HMH} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \tag{8}$$

where: ? – Poisson's number, ? – Young's modulus [MPa], $?_1$, $?_2$, $?_3$ – principal stresses. The criterion of safe material condition assumes the function (9):

$$\sigma_{red} = \frac{1}{\sqrt{2}}\sqrt{\begin{array}{c}(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{zz} - \sigma_{yy})^2 \\ +(\sigma_{xx} - \sigma_{zz})^2 + 6\left(\tau_{xy}^2 + \tau_{yz}^{+2} + \tau_{xz}^2\right)\end{array}} \tag{9}$$

where: $?_{xx}$, $?_{yy}$, $?_{zz}$, $?_{xy}$, $?_{yz}$, ??? – stress tensor components.

5 Boundary and initial conditions

The parameters at the inlet and outlet were implemented on the basis of the actual starting curves [4]. The start-up was a warm start, with the geometry being heated to 130 [4]. Initially, steam flowed through the additional inlets with the same temperature values as the main steam flow. When the temperature reached 300 , cooling was started. After this time, the temperature of the additional injection steam was constant.

Four simulations of two starts were performed for each geometry, i.e., start-up 3h and accelerated 2h.

6 Results and discussion of the Thermal-FSI analysis

The use of cooling steam injection during the 3h start-up results in reducing the impact of the high temperature field on the turbine structure. Through the use of cooling it was possible to limit the field of high temperatures to the first stage of the turbine, as shown in Fig. 4.

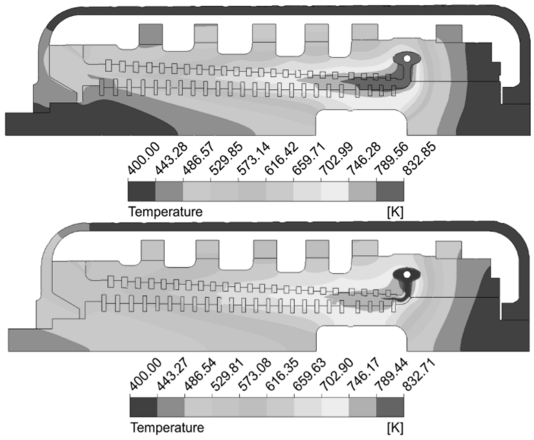

Figure 4: Distribution of the temperature field in the 180th minute of start-up 3h. Top: starting without injection of a cooling steam. Bottom: starting with injection of a cooling steam

In the case of accelerated start Fig.5, the application of cooling also results in limiting the field of influence of high temperatures, but here the temperature differences have higher values.

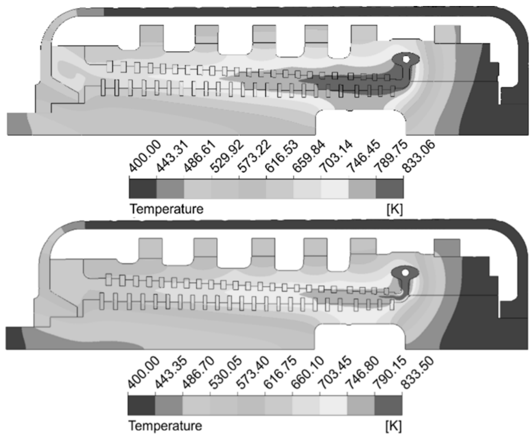

Figure 5: Distribution of the temperature field in the 120th minute of start-up 2h. Top: starting without injection of a cooling steam. Bottom: starting with injection of a cooling steam

Fig. 6 shows stress patterns during 3h and accelerated start-up.

In the initial 3h turbine start phase, the stress generated in the structure for the cooling start take higher values than for the start-up without cooling. However,

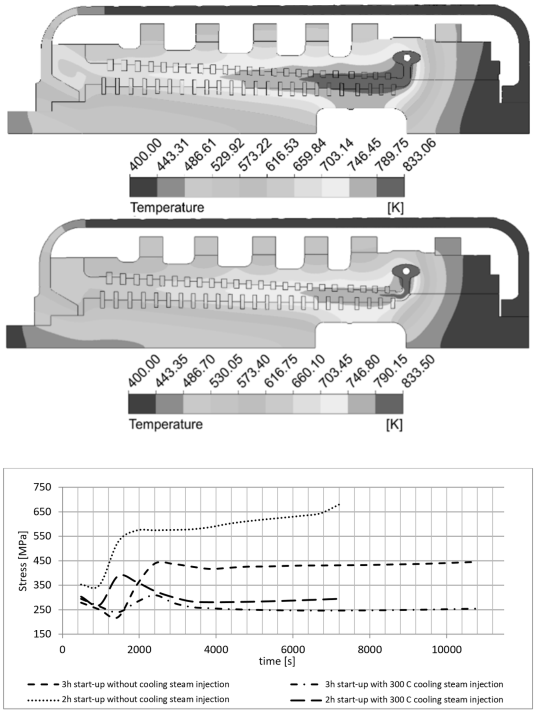

Figure 6: H-M-H stress course during turbine start-up

in the further start-up phase it can be seen that the use of cooling results in a reduction in the stress value in the structure. After approximately 1800 s (30 min) of starting, the stresses for cooling start take values around 200 MPa lower than for the start-up without cooling steam injection. The same situation as for the 3h start-up is presented for an accelerated start. The use of cooling steam injection in this case results in a reduction of the stress value by approximately 400 MPa. It is worth noting that the stresses during the accelerated cooling start take lower values than for the reference start without cooling.

7 Conclusions

The use of cooling steam injection reduces the influence of the high temperature field on the turbine structure, which translates into lower stress generated during starting. Stresses are a factor which limits the speed of regulation. In addition, it has been demonstrated that the start-up time can be shortened to 2 hours. This research sheds light on the potential use of cooling steam injection in counteracting problems associated with the increasing importance of renewable energy sources. Turbines might usefully be adapted to embrace cooling steam injection. Going forward, 3D calculations should be carried out to gain insight into the effect of additional inlets on turbine performance.

References

1.Badur, J., Kowalczyk, T., Piotr, P.Z., Ziółkowski, J., Sławiński, D., and Bryk, M. (2017) Problem elastyczności bloków cieplnych w warunkach dynamicznego rozwoju OZE. *Acta Energetica*, **2**.

2.Badur, J., and Bryk, M. (2018) Krajowe nadkrytyczne bloki weglowe: praca podstawowa czy elastyczna?. *Nowa Energia*, **62** (2).

3.Domachowski, Z. (2011) *Regulacja automatyczna turbozespołów cieplnych*, Wydawnictwo Politechniki Gdańskiej.

4.Badur, J., and Bryk, M. (2019) Accelerated start-up of the steam turbine by means of controlled cooling steam injection. *Energy*, **173**, 1242–1255.

5.Chmielniak, T. (2015) Elastyczność cieplna bloków energetycznych dużej mocy. Możliwość jej zwiekszenia. *III Konferencja Techniczna RBnPN*.

6.Kruczek, S. (2011) *Kotły. Konstrukcje i obliczenia.*, Oficyna Wydawnicza Politechniki Wrocławskiej.

7.Badur, J., Sławiński, D., Kornet, S., Kowalczyk, T., Bryk, M., Ziółkowski, P.J., Stajnke, M., and Ziółkowski, P. (2016) Pozaprojektowe ograniczenia majace na celu utrzymanie dyspozycyjności turbiny parowej dużej mocy. *Energetyka*, 652–654.

8.Kowalczyk, T., Badur, J., and Bryk, M. (2019) Energy and exergy analysis of hydrogen production combined with electric energy generation in a nuclear cogeneration cycle. *Energy Conversion and Management*, **198**, 111805.

9.Kosman, G., Rusin, A., Taler, J., and Pawlik, M. (2010) *Zagadnienia projektowania i eksploatacji kotłów i turbin do nadkrytycznych bloków weglowych*, Wydawnictwo Politechniki Śląskiej.

10.Kosman, W. (2011) Optimization of start-up conditions to reduce thermal loads in cooled components of a supercritical steam turbine. *Journal of Power Technologies*, **91**, 47–53.

11.Kosman, W. (2013) Analiza obciażeń cieplnych podczas rozruchu nadkrytycznych turbin parowych z chłodzeniem zewnetrznym. *Archiwum Energetyki*, **XLIII** (1-2), 147–155.

12.Badur, J., Bryk, M., Ziółkowski, P., Sławiński, D., Ziółkowski, P.J., Kornet, S., and Stajnke, M. (2017) On a comparison of Huber-Mises-Hencky with Burzynski-Pecherski equivalent stresses for glass body during nonstationary thermal load. *AIP Conference Proceedings*, **1822**.

13.Bryk, M., Kowalczyk, T., Ziółkowski, P., and Badur, J. (2019) The thermal effort during marine steam turbine flooding with water. *AIP Conference Proceedings*, **2077**.

14.Badur, J., Ziółkowski, P., Kornet, S., Banaś, K., Kowalczyk, T., Bryk, M., Stajnke, M., and Ziółkowski, P.J. (2017) The effort of the steam turbine caused by a flood wave load. *AIP Conference Proceedings*, **1822**.

15.Badur, J., and Bryk, M. (2017) Analysis of unsteady boiling during high-temperature body dipping in water. *IFFM Transactions*, **138**, 75–88.

16.Badur, J. (2005) *Five lecture of contemporary fluid termomechanics*, Wydawnictwo Instytutu Maszyn Przepływowych.