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EXPERIMENTAL VALIDATION OF AN ALGORITHM FOR DETERMINING TRANSIENT STRESSES WITHIN PRESSURE COMPONENTS BY MEANS OF THE TENSOMETRIC METHOD

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ABSTRACT

The article presents an experimental validation of an algorithm for determining transient stresses within pressure components which are extensively employed in industry. The algorithm is based on the solution of the Inverse Heat Conduction Problem (IHCP) and incorporates temperature measurements on the outer surface of the analysed components. For validation purposes, a laboratory stand was modernised and 19 new dedicated strain gauges (SG) were installed. The novelty of this work is the validation of calculated transient stresses on the component's outer surface by means of tensometric methods. A crucial aspect is the appropriate correction of the measured values of strains because the measure properties of SGs vary with temperature. The scope of the article covers an analysis of the stresses on the cylinder's inner surface as well. The calculated and measured values were compared to values obtained from a generalized theory of quasi-state heating, which incorporates a thermocouple located in the component wall. The agreement between all methods was satisfactory. This broadly validated in-house algorithm is suitable for comprehensive monitoring of working conditions of critical components in various industrial installations.

Keywords: power unit, thermal stress, thick-walled header, strain gauge, transient state, temperature field

NONENCLATURE

Abbreviations	
IHCP	Inverse heat conduction problem
SG	Strain gauge
S-T-C	Self-temperature-compensated
TC (TCW)	Thermocouple (embedded in a wall)

Symbols	
a	Thermal diffusivity: m^2/s
F^*	The value used by the manufacturer in recording thermal output data: -
F_{sg}	Strain gauge factor: -
$\Delta F(\%)$	Percent variation in gauge factor with temperature: %
s	Wall thickness: m
T	Temperature: °C
Greek symbols	
α	Coefficient of thermal expansion: 1/K
ε	Strain: µm/m
σ	Stress: MPa
v	Poisson's ratio: -
ϕ	Shape coefficient: -
Subscript	
1, 2	circumferential, axial direction
corr	corrected
i, (o)	inner (outer) surface
m	measured
mech, th	mechanical, thermal stress
ref	reference

1. INTRODUCTION

The methods of determining the total and thermal stresses that occur in power plants, chemical plants, oil and gas plants, etc. is an important field of mechanics. Thermal stresses are caused by temperature differences within individual elements which cause differing local levels of thermal expansion. One such field is thermal power engineering, in which thermal stresses have a significant influence on the operation and lifetime of power unit components, e.g. pipelines, valves, boilers, waste heat recovery units, and turbines. Due to the high pressure and temperature and the mass flow rate of steam, pressure components work in highly demanding conditions, especially during transient states, which often result in high thermal stresses.

The operation of industrial installations is possible thanks to control systems incorporating different kinds of measurement sensors (mass flow meters, pressure transducers, thermocouples). An important aspect is temperature measurement combined with the use of algorithms to determine total stress as a combination of both mechanical and thermal stress. The reliability and accuracy of such a monitoring method are very important in the case of thick-walled pressure components. To the best knowledge of authors, the current monitoring systems and algorithms adopt one or two temperature measuring points. Thermocouples (TCs) are usually located at the top and bottom of the monitored components, and less frequently in the component's wall at a strictly defined depth. The second approach assumes a simplification of 1-D temperature distribution, which is enough in only a few cases.

In this paper a validation of the developed in-house algorithm is presented. The algorithm allows determination of two-dimensional transient temperature and stress fields within the cylindrical shaped components. The algorithm was presented and the temperature fields were validated in a previous work [1]. In this paper the stresses are examined and validated by means of strain gauges. The novelty of this paper is usage of dedicated stacked rosettes installed in 19 points which correspond to the nodal positions defined by division of the half cross-section into control volumes.

As the literature review shows, the tensometric method is not a common method for determining stress at elevated temperatures (> 100°C). There are a few articles which incorporate strain gauges in different practical problems, such as in thermal strain measurement of a divertor embedded in an EAST Tokamak nuclear fusion reactor [2] or in a study of strain and thermal stress in a 3 mm welded plate [3]. However, the author of the aforementioned works provided only basic information regarding the tensometric method used. The most complete description of tensometric method can be found in work [4]. The authors focused on the correct uncertainty estimation of non-uniform residual stresses determined by the hole-drilling strain gauge method. However, all measurements were performed at a temperature of 23.5°C and thus the temperature influence on the strain gauges was not examined.

2. EXPERIMENT

2.1 Laboratory stand

For experimental purposes, an existing laboratory stand for a steam header was modernised. The laboratory stand had been used in many experimental campaigns presented in [5–8].

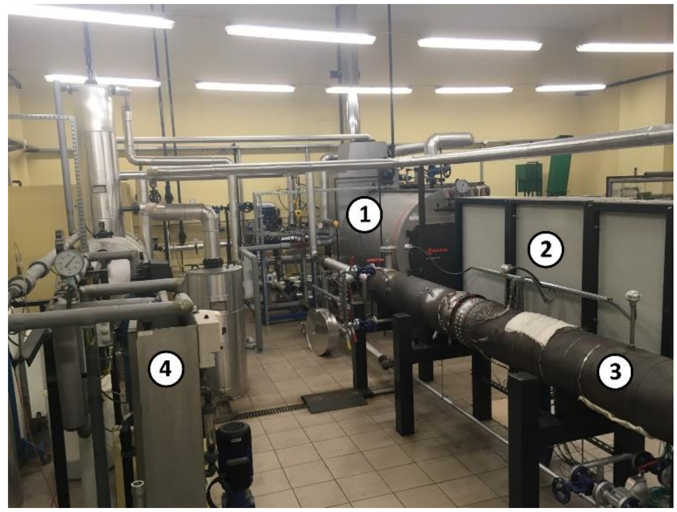

Fig 1 A general view of the laboratory stand: (1) steam boiler; (2) measuring equipment; (3) outlet header with TC and SG sensors; (4) water treatment station

Fig. 2 depicts a photo of the strain gauges and thermocouples installed on the outlet header, which is made of martensitic steel P91. In total, 19 measuring points are installed on the outlet header. In addition, 3 wall-embedded thermocouples are used to calculate the thermal stresses at the components' inner surface. More details about the experiment settings can be found in [1].

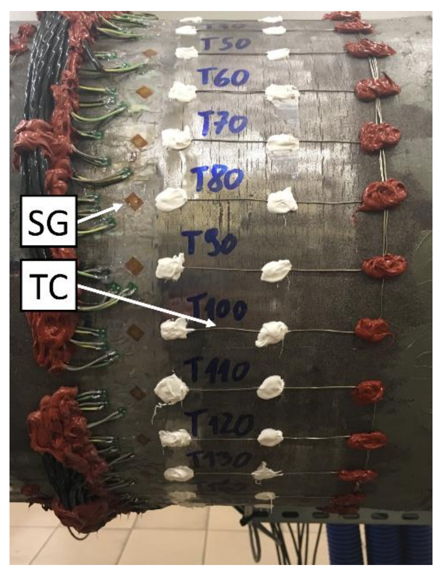

Fig 2 Strain gauges (SG) and thermocouples (TC)

The measurement installation is equipped with 6 Peltron WT-2 strain gauge amplifiers, 10 HORNER thermocouple input modules connected to the control system of the laboratory rig via the Modbus RTU protocol.

3. METHODS

3.1. The in-house algorithm

The in-house algorithm allows determination both of transient temperature and stress fields in cylindrical components. The input data for the algorithm are temperature transients measured by 19 thermocouples every second. The algorithm is based on a solution of the IHCP by means of the Control Volume method. The location of the thermocouples corresponds with the nodal positions used in the algorithm. The discretisation and formulas are presented in [1].

The values of total stresses are calculated for 19 points along the perimeter using the following formula:

$$\sigma_{total} = \sigma_{mech} + \sigma_{th} \tag{1}$$

The mechanical stresses σ_{mech} caused by internal pressure are calculated by Lamé correlation. The thermal stresses are determined by the following correlations:

$$\sigma_{th,1i} = \sigma_{th,2i} = \frac{E\alpha}{1-\nu}(T_m - T_i) \tag{2}$$

$$\sigma_{th,1o} = \sigma_{th,2o} = \frac{E\alpha}{1-\nu}(T_m - T_o) \tag{3}$$

The algorithm delivers the temperature differences for each time step considering the temperature-dependent thermophysical properties of steel.

2.3. Strain gauges

For validation purposes, dedicated strain gauges (stacked rosettes) manufactured by Vishay Precision Group (model: WK–06–060WR–350) were used. Karma alloy (K-alloy) was adopted as the strain-sensitive alloy used in the foil grid. This is recommended for extended static strain measurements over a temperature range of -269° to +260°C. For short periods, encapsulated K-alloy strain gauges can be exposed to temperatures as high as +400°C [9]. Rosettes allow strain measurement in the axial direction ε_{0°; ε_{45° and in the circumferential direction ε_{90°. Based on measured strain values, the main strains ε_{min} and ε_{max} can be calculated with Eqs. (4–5).

$$\varepsilon_{max} = \\ = \frac{\varepsilon_{0^\circ} + \varepsilon_{90^\circ}}{2} + \frac{\sqrt{2}}{2}\sqrt{(\varepsilon_{0^\circ} - \varepsilon_{45^\circ})^2 + (\varepsilon_{45^\circ} - \varepsilon_{90^\circ})^2} \tag{4}$$

$$\varepsilon_{min} = \\ = \frac{\varepsilon_{0^\circ} + \varepsilon_{90^\circ}}{2} - \frac{\sqrt{2}}{2}\sqrt{(\varepsilon_{0^\circ} - \varepsilon_{45^\circ})^2 + (\varepsilon_{45^\circ} - \varepsilon_{90^\circ})^2} \tag{5}$$

The calculated values of strains allow determination of stresses σ_{min} and σ_{max}, which correspond to axial and hoop total stress, respectively.

$$\sigma_{min} = \frac{\mathrm{E}}{1-\nu^2}(\varepsilon_{min} + \nu\varepsilon_{max}) \tag{6}$$

$$\sigma_{max} = \frac{\mathrm{E}}{1-\nu^2}(\varepsilon_{max} + \nu\varepsilon_{min}) \tag{7}$$

The equations (6) and (7) will be used in calculation of total stresses, but the measured strain values have to be corrected first. The next section presents the outline of required procedure.

2.4. Strain values correction

Strain gauge measurements are based on electrical resistance changes of a strain-sensitive alloy, which varies with the wire's deformation and with the temperature. Since the validation was performed at an elevated temperature, the temperature influence on the strain values is significant and has to be considered. The temperature correction of the strain values is explained in the manufacturer's document [9] and below there are explained the most important issues which have to be corrected:

1. Compensation for thermal output when an installed strain gauge connected to a strain indicator shows an artificial strain value caused by the temperature change. This resistance change is independent of the mechanical (stress-induced) strain in the test object. This factor is corrected using the polynomial presented in fig. 3. For each batch of the strain gauges, individual polynomial coefficients are provided by the manufacturer.

2. Correcting for gauge factor variation with temperature: The gauge factor is defined as the ratio of relative change in electrical resistance *R*, to the mechanical strain ε. The self-temperature-compensated alloy Karma requires correction of the

gauge factor when the gauge is subjected to a temperature change of more than 50°C. The correction can be done on the basis of fig. 4 depending on the S-T-C number, i.e. a group of materials with a defined range of linear thermal expansion (in the presented case, P91 steel belongs to S-T-C 06).

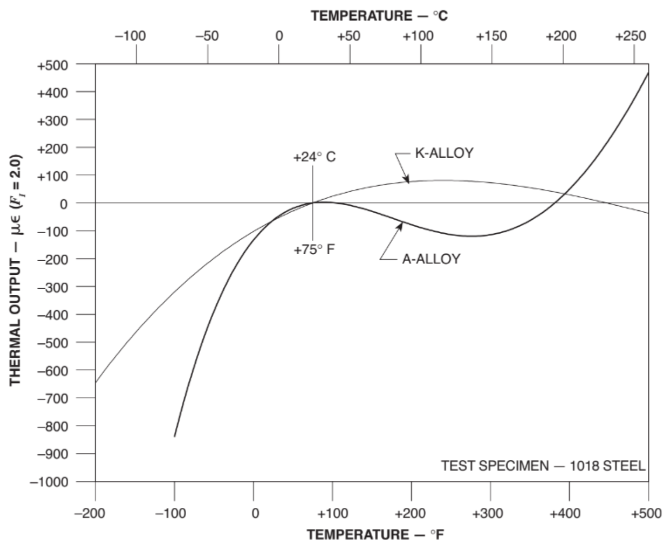

Fig 3 Strain gauge thermal output variation with temperature [9]

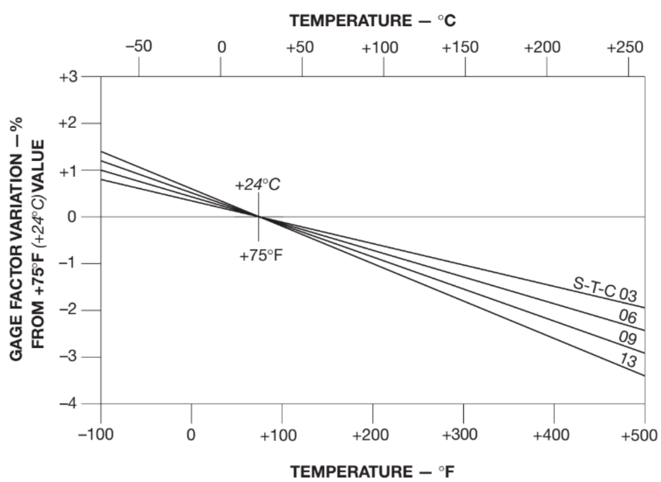

Fig 4 Variation of K-alloy gauge factor with temperature and S-T-C number [9]

Based on the manufacturer's documentation, the final correlation for the temperature correction of the measured temperatures can be written as follows:

$$\varepsilon_{corr} = \frac{F^*\left(\varepsilon_m - \varepsilon_{output\ (P91)}\right)}{F_{sg}\left(1 + \frac{\Delta F(\%)}{100} \cdot \frac{\left(t_m - t_{ref}\right)}{100}\right)} \qquad (8)$$

The corrected values ε for each direction were used in Eqs. (4–5) and the corrected values of ε_{min} and ε_{max} were used in the final calculation.

2.4. Direct measurement of heating rate

Due to the low pressure of steam flow inside the outlet header (< 5.0 bar), the mechanical stresses are negligible (< 1 MPa). Due to this fact, the stresses observed during the experiment have a thermal stress character. One method which is used for monitoring thermal stresses incorporates a thermocouple located inside the component's wall. The thermocouple has to be installed in a drilled hole at a precisely defined depth. The methodology and more explanation can be found in ref. [10]. The location of the wall-embedded thermocouple TCW1 is presented in [1]. The values of thermal stresses in a transient state can be calculated from Eq. (9).

$$\sigma'_{th,1i} = \sigma'_{th,2i} = \frac{E\alpha}{1-v}\frac{v_m(t)s^2}{a}\phi_i \qquad (9)$$

$v_m(t)$ is the current heating rate measured by the embedded thermocouple.

3. RESULTS

Strain data were collected during the heating up of the pipe by the flow of steam inside the component. The heating process lasted ca. 23 minutes, after which the cylinder was left to cool down freely and slowly. The pressure of the steam was about 5.0 bar, with a temperature at this pressure of 150°C. The mass flowrate varies from 480 to 590 kg/h. Before the heating up process, the initial temperature of the component was equal to 23°C. During the heating process, the saturated steam condenses on the internal surface. Due to presence of a thin water film created by the condensate, the heat transfer coefficient deteriorated in the bottom part of the component. Therefore, the top part of the component heated more quickly, which resulted in higher thermal strains and stresses in this region. The strain values registered in the axial direction (0°) are presented for all strain gauges in fig. 5.

It can be seen that the top part of the header was subjected to higher thermal expansion (T00-T90). The bottom part (T180) heated up much slower, which resulted in smaller strain values.

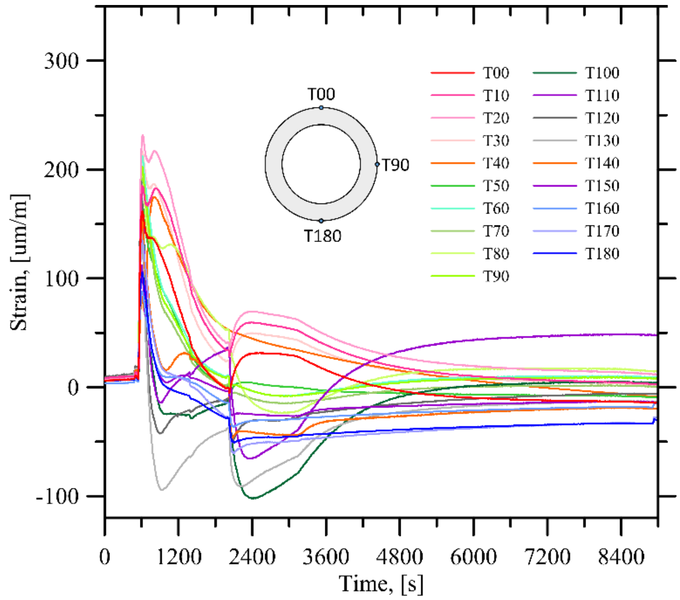

Fig 5 Axial strain transients registered by 19 strain gauges during the experiment

The obtained data were used to determine the stresses using Eqs. (4–5) and (8). Due to the limited space within this article, only point (T00) will be presented in fig. 6.

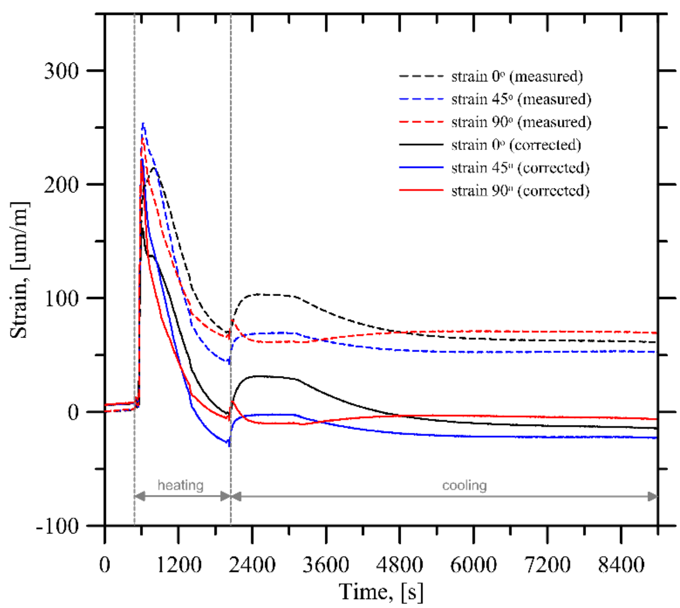

Fig 6 Measured at T00 and corrected strains in three directions during the heating and free cooling process

In fig. 6, a significant strain correction output can be observed. The correction procedure reduced the strain values to zero, resulting in stresses near zero during the cooling process. The main effect of the correction is decreasing stress values to zero, as can be observed on fig. 7.

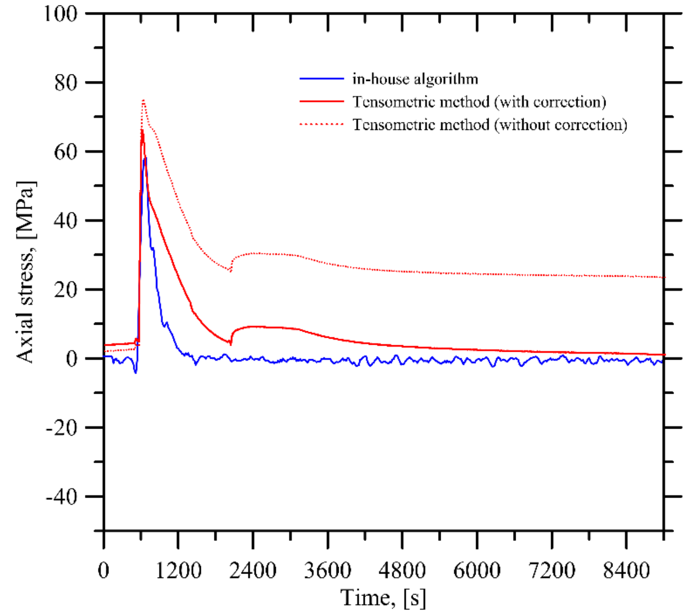

Fig 7 The stress values calculated and determined by means of the strain gauge at the T00 location

The heating process lasted ca. 23 minutes, then the control valve was closed. There were no thermal and mechanical induced stresses in the entire component during the cooling process. Both the in-house algorithm and the tensometric method show stress values equal zero during the cooling process.

Fig. 7 depicts the stress value of the non-corrected data. It can be seen that the strain registered during the cooling process was obviously caused by thermal expansion. The main intention of using dedicated strain gauges and correcting their outputs is to 'extract' the strain which induces the real value of thermal stress (or total stress in the case of higher-pressure fluid inside the component). To remove any temperature influences on strain measurement, the gauge can be installed in a Wheatstone bridge with a dummy gauge; however, in this scenario the measured output would correspond to the mechanical strain induced by internal pressure. Thus, an S-T-C strain gauge installed in a quarter-bridge arrangement can be used to determine total and thermal stresses.

When the outer surface was subjected to tensile stress, the inner heated surface was subjected to compressive stress, as can be observed in fig. 8. In addition, the stresses at the inner surface have significantly higher values during the thermal shock caused by the steam condensation.

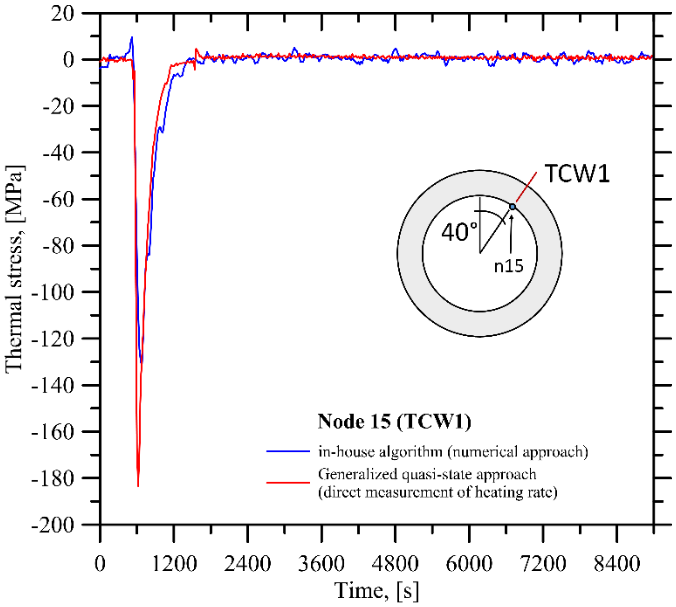

Fig 8 The stresses at the inner surface of the outlet header determined by the in-house algorithm and a general quasi-state theory

The stress transients presented in fig. 8 are basically thermal stresses only. The thermal shock caused a high peak in the values, and then the absolute value dropped to zero when the cooling process started. A good agreement between the in-house algorithm and the general theorem of quasi-state heating was observed. However, the latter approach overestimates the stresses' values in a case of thermal shocks. The results obtained from TCW2 and TCW 3 (not presented in this paper) have a satisfactory degree of agreement. The results obtained from the other 18 strain gauges showed slightly worse convergence, but due to limited space the results are not presented in this version of the paper.

4. CONCLUSIONS

The experiment consists in rapid heating of a thick-walled header by a steam flow. The stresses on the outer surface were calculated by an in-house algorithm and validated by the tensometric method. Stresses on the inner surface were calculated and compared with values obtained from the generalized theory of quasi-state heating. Based on the results, the following conclusions can be made:

1. The stresses calculated by the in-house algorithm are in good agreement with the values obtained by the strain gauges.
2. Temperature correction and proper installation of strain gauges allow determination of transient thermal stress.
3. The transient stress distribution within the element can be calculated with the algorithm on the basis of temperature measurements.
4. The stresses determined by the algorithm at the inner surface show a satisfactory convergence with the method based on wall-embedded thermocouple measurement.
5. The main output of the performed research is a validation of the in-house algorithm which can be used in control systems in industry plants.

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