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Evaluation of the effects of the operation strategy of a steam power plant on the residual life of its devices

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A B S T R A C T

In the deregulated market scenario wider power generation flexibility with respect to the past is needed; on the other hand, frequent changes of the operating conditions may reduce the life of the most critical components, such as steam heaters or turbine blades. Fatigue failures produced by cyclic thermal and/or mechanical stresses will be considered in this work. The estimation is based on creep and fatigue failure models and is applied at the component level. In particular, in this paper evaluation of the impact of thermo-mechanical fatigue in the superheater pipes of an actual coal power plant will be carried out to estimate its residual life. Then, this evaluation at the device level will be translated into plant level assessment.

Actually, the last aim of the work is developing an on-line real-time procedure suitable to determine how the present operation choices may influence the residual life of the components and of the whole plant and how to manage the plant under design and off-design conditions. These results are helpful in order to optimise the plant operation over time, assess components state, plan its production schedule, and forecast the expected performance degradation.

1. Introduction

It is well known that the optimum design and/or management of a plant or of a set of plants must be "lifetime oriented" [1]: it has to reach the best average performance during the whole life of the system.

This point of view brings much more difficulties in the analysis than a fixed point study because many different variables and uncertainties must be considered. For this reason, often the complex global problem is simplified, considering only the aspects that are considered the most crucial at a given moment. Many different approaches have been proposed in the literature, regarding, for example, the optimisation of only the energetic performance or the environmental impact or the profit, and considering each plant as alone or the whole system but simplifying the operation of its single subsystems. Sometimes plants operation is considered as a sequence of steady conditions; at other times the operation during transient periods is included in the analysis [2–5].

In this paper, attention is focused on the relationship between plant operation and its components' residual life. This relationship has been implemented in a proper methodology for the optimisation of long-term plant performance.

The recent introduction of a liberalised energy market in Italy has brought new strategies in plants and systems management: very irregular and discontinuous operation of power plants is requested in order to meet the users demand and produce energy only during peak hours, when the electricity price is higher [6]. For these reasons, today all power plants are asked to adopt this strategy, also those designed for base load operation, as the (old) big steam power plants. This operation mode can supply a greater income in the short period, but is likely to cause lifetime reduction of the most critical components, due to creep and thermo-mechanical fatigue loadings and consequent serious long-term profit losses deriving from the extra costs associated with unplanned maintenance and the unavailability of the plant if a failure occurs [7–11].

The procedure proposed [12] by the authors for the power plant on-line monitoring, control, production and maintenance scheduling, considers this kind of question and can be divided into five steps. The last is a feedback level, whose results can suggest modifying the starting point of the analysis:

1. Market level: the independent variables are the plants production schedules to be traded in the spot market.
2. Plant level: once the market level variables have been chosen depending on the objectives of the power producer, these

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Nomenclature

D	fatigue or creep damage
E	modulus of elasticity
N	number of cycles due to fatigue loadings
N_0	number of cycles to failure
P	electric power [MW]
T	temperature [°C]
d	annual rate of fatigue or creep damage accumulation
p	pressure [MPa]
r	radius [mm]
t	time [h]
t_r	time to failure [h]
α_{th}	thermal expansion coefficient [°C^{-1}]
$\Delta\varepsilon$	strain range (difference between the maximum and minimum value during a strain cycle)
ε	strain
μ	Poisson's ratio
σ	stress [MPa]
σ_{ss}	Von Mises equivalent stress [MPa]
Subscripts	
L	limit
c	creep
f	fatigue
j	generic fatigue cycle
k	generic creep level (temperature)

strategies are forced at the single plant level, by fixing the plant's independent variables (power, set-points, control variables, etc.).

3. Process level: the plant's independent variables control the thermodynamic variables, which define the energy conversion process. As a consequence of the previous levels, specific trends for the thermodynamic data variables are fixed and need to be verified during the real operation or forecasted by proper models.
4. Mechanical assessment level: the variation over time of the thermodynamic variables determines the associated trend of the underlying mechanical parameters (stress and strain variables in each component). These variables are used to calculate the cumulative mechanical damage of each component. The effect of the current management strategy is therefore evaluated in terms of residual life reduction.
5. Feedback level: by comparing the short-term advantages of the strategy with the longer-term drawbacks (e.g. reduction of the expected time before the next maintenance) it is possible to modify the market strategy in order to have the best economic performance over extended periods of time.

This paper emphasizes in particular the model to evaluate the impact of creep effects and thermo-mechanical fatigue on the components' residual life (step 4), starting from the operation strategy of the plant. As in Italy 25% of the electric production comes from steam power plants and in these plants the boiler, and above all the high temperature superheater [13,14], is very critical because of its high temperatures and pressures, the model has been first of all applied to this component. The results will be reported in this paper.

An example of the application of the complete procedure will be also presented in the paper: the effects of two different production plans on the life of the superheater will be compared. These results will be then used to evaluate the annual net return of the plant for each strategy in the next 20 years in order to find out the best long-term approach.

2. Models for creep and thermo-mechanical fatigue

2.1. Model for creep damage assessment

According to Refs. [5,15–23] in the dwelling cycle at high temperature the creep damage after a time t_h is the following:

$$D_c = \frac{t_h}{t_r(\sigma_{ss})} \tag{1}$$

where $t_r(\sigma_{ss})$ is the time to failure at the equivalent stress σ_{ss}; σ_{ss} is calculated according to Von Mises equivalent stress in the multi-axial strain state. The expression for t_r is:

$$t_r = m(\sigma_{ss})^{-n} \tag{2}$$

where m and n are linked to the material properties, depending on the temperature [15,24,25].

2.2. Model for fatigue damage assessment

In mono-axial loading, the total fatigue damage D due to cyclic strain ranges $(\Delta\varepsilon)_j$ is defined as [15,16,26–32]:

$$D_f = \sum_j \frac{N_j}{(N_0)_j} \tag{3}$$

where $(N_0)_j$ is the number of cycles leading to a crack size a_0 under a cyclic strain range $(\Delta\varepsilon)_j$.

Usually, fatigue strength data are given in the form $N_0 = f(\Delta\varepsilon)$, where N_0 is the number of cycles to a complete failure achieved in laboratory tests. For the steel SA213TP321H used in the superheater of the present analysis, this relationship (the so-called Manson Coffin curve) has been experimentally obtained by the authors [15,33,34].

Under multi-axial loading conditions, it is necessary to calculate the Tresca and Rankine equivalent strains [17,35] according to the following expressions:

$$\Delta\varepsilon_{eqRankine} = \frac{1}{(1+\mu)}\left[\Delta\varepsilon_1 + \frac{\mu}{1-2\mu}(\Delta\varepsilon_1 + \Delta\varepsilon_2 + \Delta\varepsilon_3)\right] \tag{4}$$

$$\Delta\varepsilon_{eqTresca} = \frac{1}{(1+\mu)}(\Delta\varepsilon_1 - \Delta\varepsilon_3) \tag{5}$$

where $\Delta\varepsilon_1$, $\Delta\varepsilon_2$, $\Delta\varepsilon_3$ are the ranges of principal strains.

2.3. Model for creep–fatigue damage assessment

The accepted model suggests adding fatigue and creep damage using a linear rule:

$$D = D_f + D_c < D_L \tag{6}$$

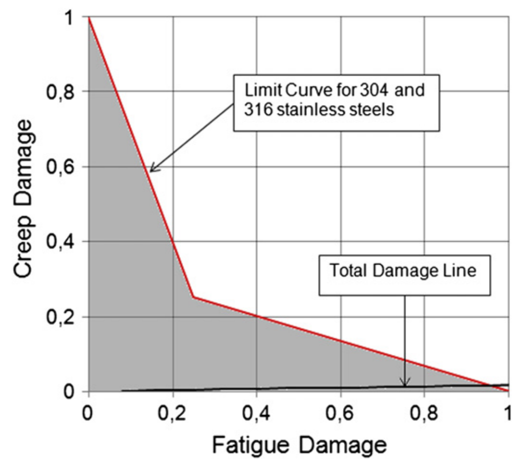

Fig. 1. Cumulated creep–fatigue damage according to the ASME code.

$$D = \sum_{j=1}^{p} \left(\frac{N}{N_0}\right)_j + \sum_{k=1}^{q} \left(\frac{t_h}{t_r(\sigma_{ss})}\right)_k \leq D_L \tag{7}$$

and last,

$$D_L = d_L n_{year} = d_f n_{year} + d_c n_{year} \tag{8}$$

where D is the total creep–fatigue damage and D_L is the "limit damage" defined for different materials according to the ASME code [17], which accounts for creep and fatigue interaction, while d represents the damage accumulated in one year operation and n_{year} the life (in years). In Eq. (7), the first addendum refers to the different fatigue cycles occurring during the operation, the second to the creep damage at all the process temperature levels. Imposing $D = D_L$ in Eq. (8), the residual life can be calculated (see Fig. 1).

3. Simulation of thermo-fatigue damage

3.1. Boundary conditions

In a previous paper [15] the authors evaluated the strain and stress conditions in a linear pipe of a superheater of a sub-critical coal power plant, but the thermal fatigue had not been considered [11]. In this paper this limitation has been removed using a well-known software, Ansys Workbench™ [36], to simulate its share in the total damage and in the residual life for different operation modes.

Ansys Workbench™ [36] permits performing several types of analyses. In the present work static structural analysis and transient thermal analysis have been considered. The first one determines the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effect. The types of loading that can be applied in a static analysis include external forces and pressures, steady-state inertial forces (gravity), imposed displacements and temperatures (for thermal strain). Transient thermal analyses determine temperatures and other thermal quantities that vary over time.

The software gives the possibility to modify different properties for geometry, material data, thermal characteristics and loads.

A smooth vertical pipe without curves about 22 m long of the superheater of a 320 MW steam power plant has been analysed [37,38]. The pipe has been simulated as a cylinder made of austenitic steel (SA213TP321H). Note that the first and the last part of real superheaters are often pipes made of different steels (ferritic steel AISI A213T22) and diameters. Also the central part is not a single diameter pipe but there are three different pipes welded together. In this work the smaller diameter (external diameter = 51 mm; inner diameter = 38.2 mm) has been considered to evaluate the maximum strain and stress conditions. The pipe has been hung from one extremity with a fixed face (prevents one or more flat or curved faces from movements or deformation) and the simulation has been performed in a generic section at 3 m from this edge, where there are no interactions with the linking zone. Then the load and thermal conditions were defined using the functional data of a real coal power plant:

- weight of the pipe: 1600 N;
- internal pressure (steam pressure against the walls): from 17.5 MPa to 5 MPa (from full load to hot stop);
- internal steam temperature: from 540 °C to 300 °C;
- flue gas temperature: from 1300 °C to 900 °C;
- inside and outside convection coefficients (Figs. 2 and 3).

All physical and mechanical steel properties such as Young's modulus, Poisson's ratio, density, tensile yield strength, tensile ultimate strength and thermal expansion have been evaluated with experimental tests [15]; thermal conductivity, and specific heat were found in the literature [15,25,38–40]. All these properties are temperature-dependent.

3.2. Software simulations

Thermo-mechanical fatigue in superheaters is due to the temperature variation during startings and shutdowns. Thermal strain has been computed during a temperature modulation of 5 h in the structural analysis of Ansys™ [36].

To evaluate the strain for temperature differences the software considers a classical theory of thermal strain [38]. If the material is constrained in only one direction, the stress developed is:

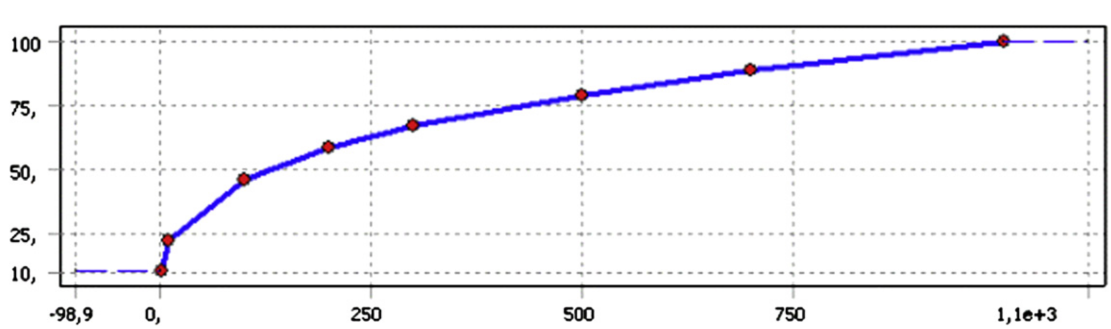

Fig. 2. Flue gas convection coefficient [W/m^2] versus temperature [°C].

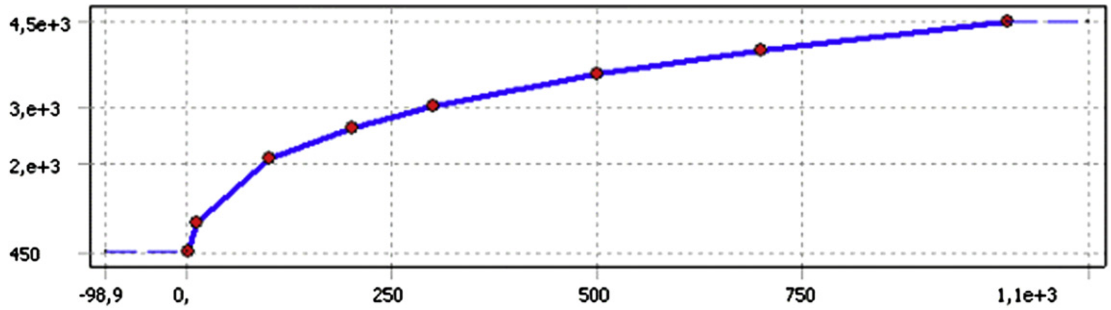

Fig. 3. Steam convection coefficient [W/m^2] versus temperature [°C].

$$\varepsilon_{th} = \alpha_{th}\Delta T \tag{9}$$

where ε_{th} is the thermal strain in one of the directions x, y or z. If the pipe is constrained from expanding or contracting in two directions, as is the case in pressure pipes, the resulting stress depends on the Poisson's ratio too. The general equations for radial, tangential and axial thermal stresses in a vessel under a radial thermal gradient are:

$$\sigma_r = \frac{\alpha_{th}E}{(1-\mu)r^2}\left(\frac{r^2-a^2}{b^2-a^2}\int_a^b Trdr - \int_a^r Trdr\right) \tag{10}$$

$$\sigma_t = \frac{\alpha_{th}E}{(1-\mu)r^2}\left(\frac{r^2+a^2}{b^2-a^2}\int_a^b Trdr - \int_a^r Trdr - Tr^2\right) \tag{11}$$

$$\sigma_a = \frac{\alpha_{th}E}{(1-\mu)}\left(\frac{2}{b^2-a^2}\int_a^b Trdr - T\right) \tag{12}$$

where a is the inside radius and b is the outside radius.

These thermal strain equations consider full restrain and therefore give the maximum strain that can be reached.

First of all the pipe under fixed load conditions (100% and 33% of nominal power) has been simulated to calculate Von Mises equivalent stress and to evaluate creep damage. As shown in Fig. 4, at 100% load the most critical section is the area of the internal radius and the equivalent stress is equal to 73.5 MPa.

Then the starting and the shutdown have been simulated in 4 and 5 h. The comparison doesn't give any relevant differences. In Figs. 5–7 the gradient temperature during shutdown from a steam temperature of 540 °C to 300 °C in 5 h is displayed.

In Fig. 8 the results of the thermal strain simulation during shutdown are shown. The simulated value in the inner radius $\varepsilon = 0.0041$ has been used to evaluate the fatigue damage with Eqs. (4) and (5) as explained in Section 4.

4. Application to a 320 MW coal-fired steam power plant

4.1. Evaluation of superheater service life

Pressure and temperature data collected in Fusina 320 MW steam power plant (Venice, Italy) have been used to calculate the stress and strain cycles [15].

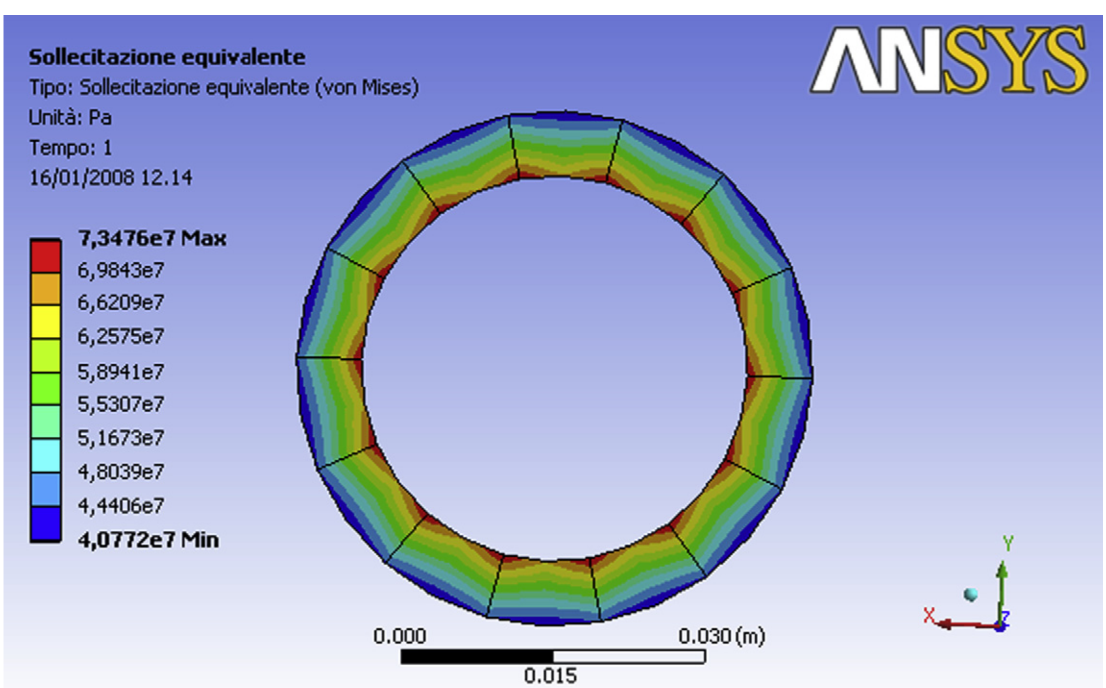

Fig. 4. Von Mises equivalent stress in a specific section of the pipe at 100% load.

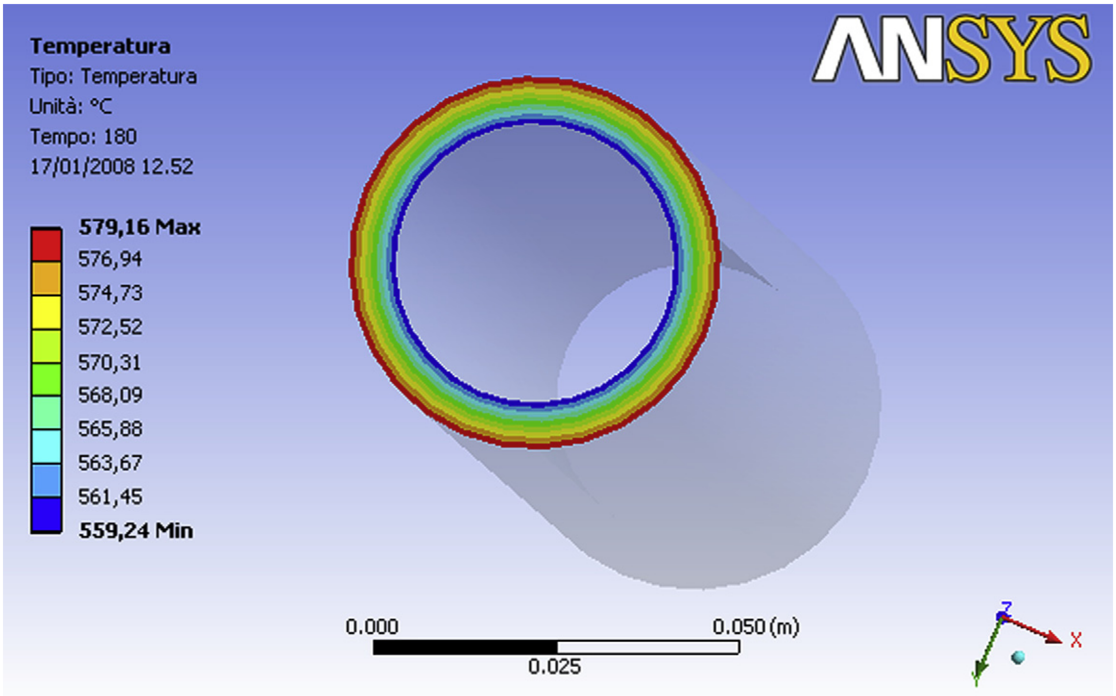

Fig. 5. Temperature gradient at the beginning of shutdown (5 h).

The first step of the proposed procedure (*market level*) suggests maximizing the profits in a short period in the deregulated energy market and so the plant has to produce only during peak hours and peak days of the week.

According to the second step (*plant level*), two different operation modes have been considered:

- Case 1: nameplate load operation by day (from 6.00 AM to 12.00 PM) and a reduction to 2/3 load by night (from 0.00 AM to 6.00 AM). In this kind of modulation creep conditions are constant and there is no fatigue cycle, because no steam temperature and pressure variations occur. This is a typical operation mode of a base load power plant.

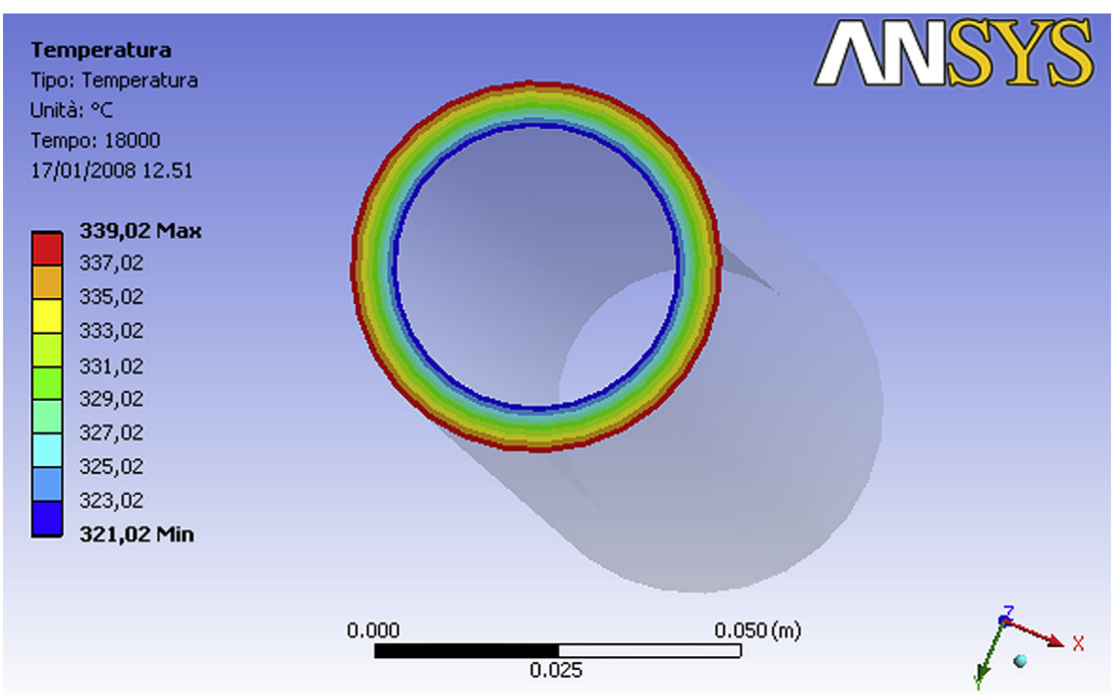

Fig. 6. Temperature gradient at the end of shutdown (5 h).

Fig. 7. Temperature on the external diameter (upper line) and inner diameter (inferior line) during a power shutdown (18,000 s).

- Case 2: nameplate load operation by day with a reduction to 1/3 load by night (Fig. 9) and a hot shutdown during the weekend (Fig. 10) (from 0.00 AM of Saturday to 6.00 AM of Monday).

To reach these proposed performances the *process level* suggests a different range of values of the principal steam thermodynamic variables (pressure and temperature):

- full load condition: $p = 17.5$ MPa, $T = 540$ °C and $P = 320$ MW;
- 2/3 load condition: $p = 17.5$ MPa, $T = 540$ °C and $P = 180$ MW;
- 1/3 load condition: $p = 12.2$ MPa, $T = 540$ °C and $P = 100$ MW;
- hot stop: $p = 5$ MPa, $T = 300$ °C and $P = 0$ MW.

The residual life of the superheater for the two different plant operations is possible because pressure and temperature variations are linked to creep and thermo-mechanical fatigue damage on the component as required in the fourth step of the procedure, the so-called *mechanical assessment level* and as explained in Section 3. In case 2, every year there are two stress levels responsible for creep damage and 47 cycles of start-up and shutdown responsible for thermo-mechanical fatigue. According to the procedure [12,15] and with the results of simulations, two different creep lives have been calculated: at full load temperature (540 °C) $t_r = 3.538\text{E}+6$ h, while at a reduced temperature (300 °C), corresponding to no load, $t_r = 2.65\text{E}+7$ h.

Concerning fatigue damage evaluations, Table 1 reports the range of the equivalent strains evaluated according to the Tresca and Rankine equations and to the values of simulation of thermo-mechanical fatigue (Fig. 8). The number of cycles to failure evaluated from these data is displayed in Table 2.

By using these data, the following damage accumulation rate (damage accumulated in one year) can be calculated (Eq. 7):

$$d_{\text{Case1}} = \left(\frac{8000}{3,538,000} + \frac{1}{600}\right) = 0.00393$$

$$d_{\text{Case2}} = \left(\frac{4300}{3,538,000} + \frac{1420}{26,500,000} + \frac{47}{600}\right) = 0.0796$$

The corresponding value of the cumulated damage D_L in ASME failure curves (Fig. 1) is equal to 0.5445 (case 1) and 0.9691 (case 2) by Eq. (8). This D_L leads to the following evaluation of the residual life of the analysed component: 137 years for case 1 and 12.2 years for case 2. The damage due to thermal fatigue is responsible for the decreased in-service life of the superheater.

4.2. The feedback level: economic analysis

These results can be translated into economic terms, taking into account electricity prices in the market, coal purchase prices, maintenance costs and CO_2 emissions costs.

According to the Kyoto protocol for the period 2008–2012, the annual CO_2 emission share has been calculated using the Italian National Emission Plan [41], that is:

$$Q = E_{2005}\alpha T_i \tag{13}$$

It depends on the plant energy production in 2005, on a specific emission coefficient α and on a decreasing coefficient T_i. With Eq. (13) the plant has to decrease its production to almost half without buying shares or paying fines. On the other hand we calculated the real CO_2 emission using the specific value 0.946 g CO_2/kWh for standard Italian coal-fired plants.

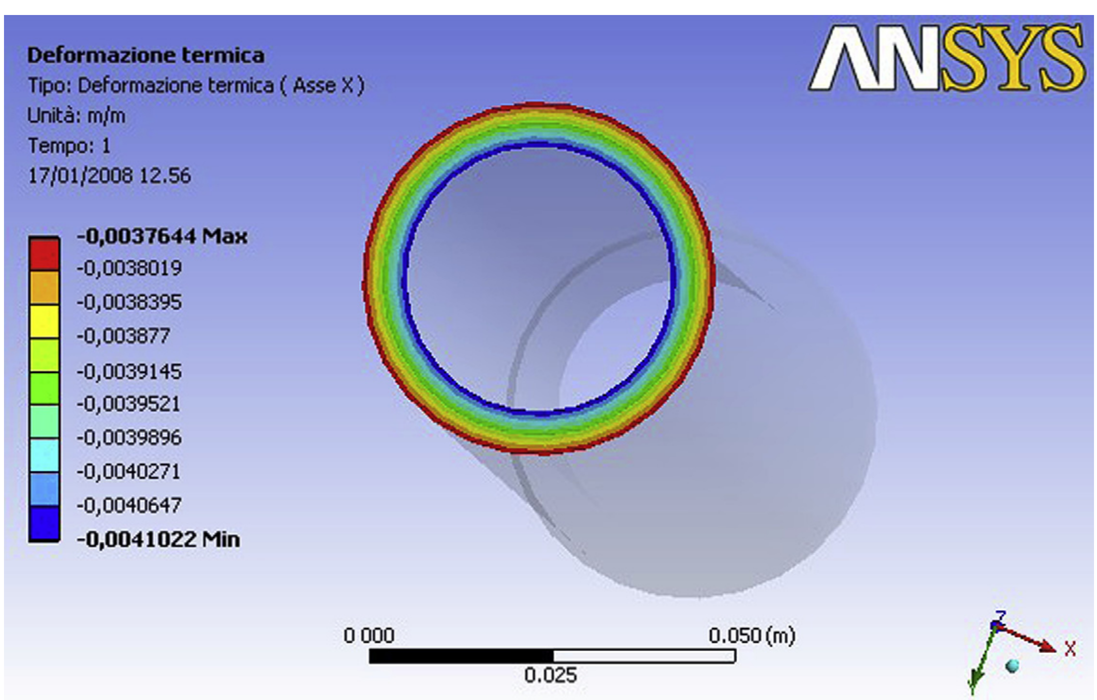

Fig. 8. Thermal strain at the end of a shutdown (5 h).

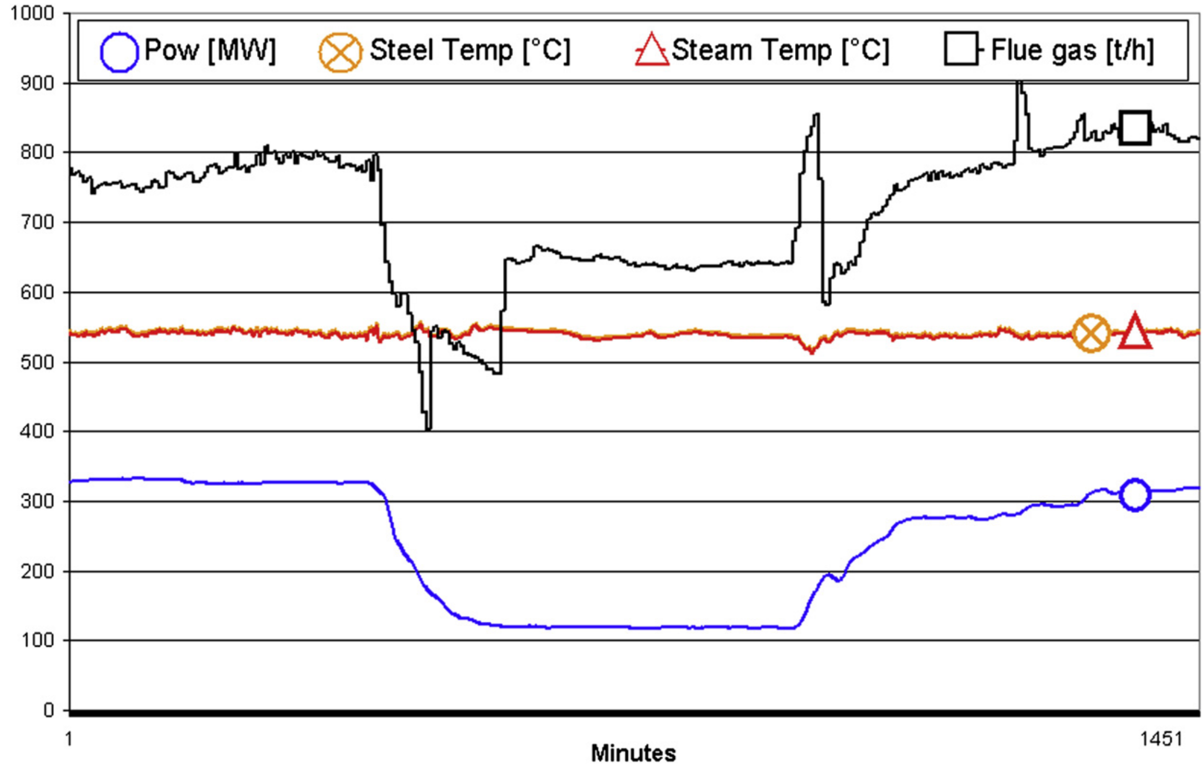

Fig. 9. 1/3 Load modulation by night: effects on steam and steel temperature.

The price of CO_2 emissions is defined by International Emission Trading. The trend rate is going down and we considered a price of 25 €/ton of CO_2 for our analysis. Moreover the fine to go over the annual CO_2 share emission without buying any external share will be near 100 €/ton.

The energy selling price has been evaluated for the peak (Monday-Friday) and off-peak days (Saturday and Sunday) and peak and off-peak hours as annual average value. It is reasonable to think that in the few next years these prices will increase with a different

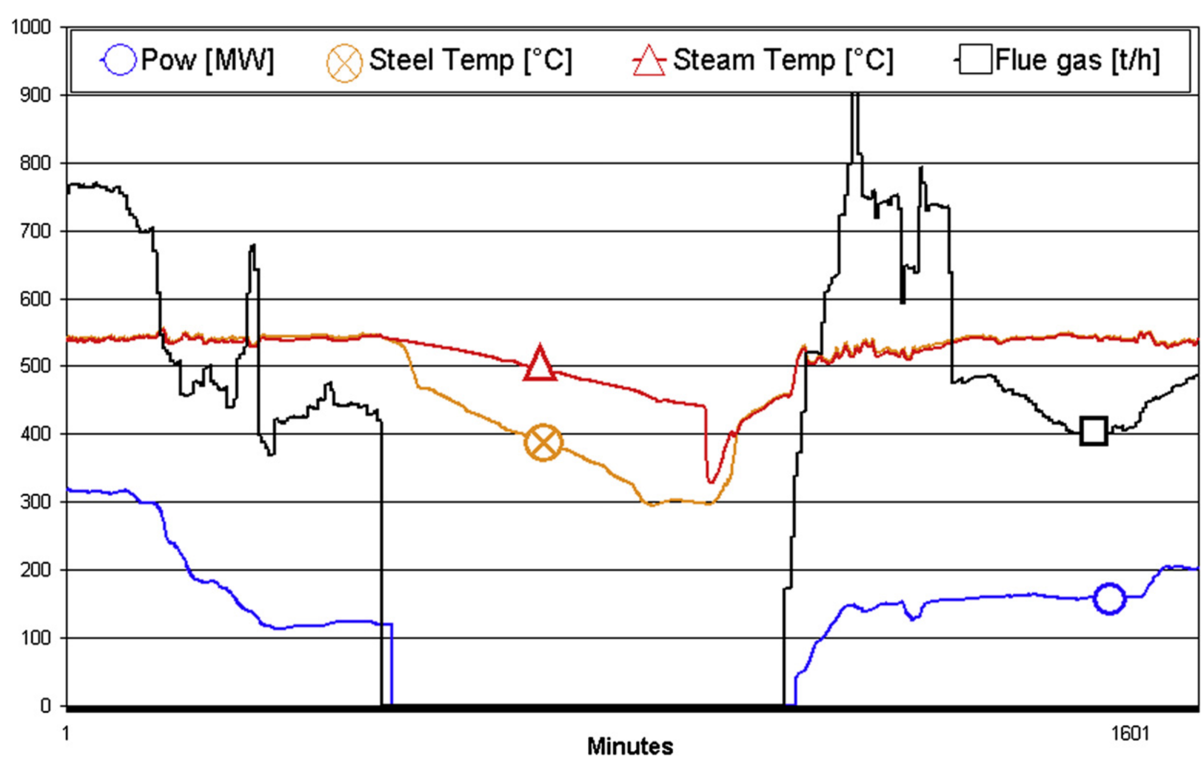

Fig. 10. Weekend power off: effects on steam and steel temperature.

Table 1
Computed equivalent strains.

Modulation	$\Delta\varepsilon_{eqTresca}$ [με]	$\Delta\varepsilon_{eqRankine}$ [με]
Power off	3464	5237
1/3 Load	416	673

Table 2
Number of cycles to failure.

Modulation	N_1 Tresca	N_1 Rankine
Power off	3200	600
1/3 Load	>1E+8	1.27E+7

rate for off-peak (+4%) and peak (+7%) hours because of the presence of the energy market.

Coal average cost is an estimation in the present situation made by Italian GME (electric market operator) and it is based on coal strike price connected with the quality and origin of coal used in Fusina power plant [15].

For the general costs (fuel excluded), we considered O and M, taxes, external services, depreciation, start-up additional costs of a common sub-critical coal power plant.

4.3. *The feedback level: economic comparison*

To compare the two different strategies of the Fusina plant management, the annual cash flow and the net present value have been used (Figs. 11 and 12). For these evaluations, the actual selected rate was equal to the European official discount rate, an average rate fixed by the BCE (3.5%). Moreover the value of a bench of superheaters is about 1.2 M€ and the substitution needs 480 h.

Case 1 leads to a greater exploitation of the plant and this reduces specific costs. At the same time it presents a smaller profit on the price of the sold energy because the energy is sold both in appreciated hours and in less remunerated hours. Case 2 allows maximum exploitation of the energy because it is almost exclusively sold in the hours of greatest merit. In the few next years the greater specific profit of case 2 will increase because of the different rate of growth calculated.

Case 1 presents a lower total damage of superheaters than case 2 but it is not economically convenient because of the greater

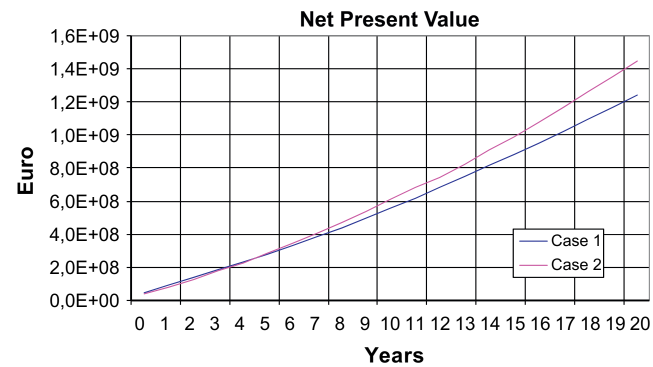

Fig. 12. Net present value for the two management cases.

expenses for CO_2 emissions and the greater exploitation given to energy.

So in case 2 the decreased residual life of the superheaters for off-design management constrains the plant to one stop in a period of 20 years but it has a positive economic return in both short and long periods.

5. Conclusions

The design procedure has been implemented to estimate the fatigue life of superheater pipes in a power plant, in particular in the presence of big temperature variations. In this work, creep and fatigue stress and strain have been evaluated by Ansys Workbench™ 11.0 software simulations. The criteria presented in the R5 and ASME code have been used for damage evaluation. For the superheater pipe under analysis both of them lead to similar results and highlight that creep damage accumulation is lower than fatigue damage accumulation, as we expected. The outlined procedure can be applied to estimate the impact of a given production plan on the lifetime of power plant's components.

In the real situation other elements can worsen the superheaters conditions: external high temperature corrosion, formation of internal oxide and flue gas erosion. All of these bring about decreased thickness of the pipes and increased wall internal temperature. These two events would have a pejorative effect on creep and so on case 1 where creep damage is higher. Future work

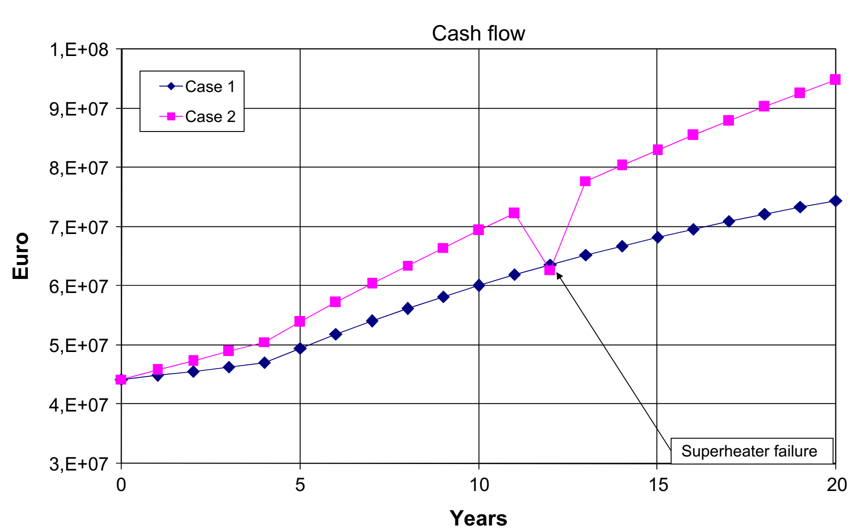

Fig. 11. Cash flow for the two operation modes (Fusina power plant).

is planned to deepen the effects of corrosion, internal oxide formation and erosion on creep damage.

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