Loss of Stability of and Damage to the Coils of Platen Steam Superheaters

V. A. Bogachev*, A. N. Samodurov*, and A. V. Tarzanov

* All-Russia Thermal Engineering Institute (OAO VTI), Avtozavodskaya ul. 14/23, Moscow, 115280 Russia

Novocherkassk district power station, OAO OGK-6, Donskoi township, Novocherkassk, Rostov oblast, 346448 Russia

Abstract—We present an investigation of damage to DI-59-grade austenitic steel coils used in the high-pressure first-stage steam superheater of a TPP-110 boiler that occurred in the form of residual sag and corrosion cracking caused by restraining and loss of longitudinal stability.

DOI: 10.1134/S0040601508020080

The range in which the temperatures of coolant and steam superheater coils fluctuate under the base operating conditions of boilers at thermal power stations is relatively narrow. The coolant is in a single-phase state during this period. The kindling of a boiler entails considerable fluctuations and excursions of the temperatures of coolant and steam superheater coils, which may be as large as several tens of degrees. The coolant may be in a two-phase state during a certain period of time. The difference in the levels of heat transfer and cooling rate between different coils occurring under the conditions of a header-type coolant distribution and collection system may cause the additional stresses in and the damage to elements.

A TPP-110 once-through supercritical-pressure boiler operates predominantly on gas. The first-stage high-pressure platen steam superheater (PSS-1), which is oriented vertically in space, comprises 16 screens. Coolant flows into screens Nos. 5–12 and flows out from screens Nos. 1–4 and Nos. 13–16. Each screen consists of 32 two-pass coils; the first and second passes are connected by means of a horizontal section. Coils 1–6, 29, and 30 perform a ranking function: they prevent the other coils from going away from the screen plane if thermal nonuniformity occurs. Most coils, except ranking coils 1–6, have an inverted Π shape. The inlet and outlet headers are oriented horizontally and connected according to a Π-shaped arrangement. The coils with odd numbers are arranged in the inlet header along the bottom generatrix and enter into the outlet header at an angle of approximately 45° with respect to the bottom generatrix; the coils with even numbers are arranged in the inlet and outlet headers in the inverse order. The coils have a size of $32 \times 6$ mm and are made of 10Kh13G12BS2N2D2 (DI 59) heat-resistant and refractory austenitic steel [1]. The vertical parts of the coils in the heated zone have a mean length of 6.3 m, and the longitudinal pitch between the coils is equal to 35 mm. The 3-mm design gap serves to prevent restraints from occurring provided that the temperature difference between the neighboring coils does not exceed 25°C.

When the boiler operates in the base mode, the coolant at the outlet from the PSS-1 screens has a pressure of 26 MPa and temperature of 510–520°C. The coolant temperature is regulated by means of an injection steam desuperheater installed upstream of the PSS-1. The steam superheater has been in operation for 2650 h.

After the boiler had been shut down, it was found that some vertical sections of second-pass coils with even numbers in inlet screens Nos. 5 through had considerably sagged. The maximum residual sag was equal to 60 mm. Gaps with a width of up to 20 mm had appeared between the horizontal sections of individual screen coils in the lower zone of the PSS-1. It should be pointed out that the coils of the second-stage high-pressure platen superheater (PSS-2) situated next along the flow of flue gases, also made of DI 59 steel, had no sags. The PSS-1 and PSS-2 screens have similar designs. The cosinelike shape of the bent axis and the residual gap indicate that the longitudinal stability became upset and that the proportionality limit and yield strength of the metal were exceeded. The difference of temperatures between the neighboring coils exceeded its admissible value.

Samples were cut out at the same level from the second-pass coil sections of the PSS-1 without sag and in the maximum sag zone. The metallographic sections were etched in a 10% aqueous solution of oxalic acid. The microstructures the coil metal had on the external surface and in the middle of the wall of the undeformed coil part were identical to one another and had primary carbides and carbonitrides. The isolation of secondary phases as a reaction to the operating conditions is in its initial stage. The surface layer of metal had insignificant corrosion damage.

A structurally altered layer was revealed in the metal on the external surface of the deformed part of the PSS-1 coil. The microstructure of metal in the middle...
of the wall contains no secondary phases. The surface layer of metal is pierced with numerous cracks, which have circumferential orientation and develop along the grain boundaries. This kind of damage is typical for stress corrosion cracking. The cracks are localized within the confines of the structurally altered layer of metal. The tensile stress on the deformed coil’s external outline is caused by the bending moment of the axial compression force resulting from the difference of temperatures between the neighboring coils, restraint, and loss of longitudinal stability of the coil section with a higher operating temperature. At present, it appears impossible to determine the nature of the structurally altered layer, as well as the level of temperature and stress in the coil metal, due to the lack of structural criteria for Steel DI 59.

The evolution of sag and stresses in the metal of coils during operation was investigated theoretically. The coil section with the initial length \( l_0 \) situated between two rigid supports is schematically shown in Fig. 1. The initial gap between the section and support is denoted by \( \delta \) and the distance between the supports, by \( l \). Heating causes the coil section between the supports becoming longer, the gap becoming zero, and the coil section being restrained between the supports, giving rise to an axial compression force and a bending moment in the supports. As is well known, if the compression force applied to a straight rod reaches Euler’s critical force, the rod loses its longitudinal stability and bends [2]. The critical load depends on the way in which the rod is fixed in supports and on the rod length and stiffness. In our further analysis, we used the energy method: the axial compression force \( p \), sag \( f \) and longitudinal stresses \( \sigma \), in the metal before and after the critical limit after the loss of stability during the heating of the coil part with a gap were determined analytically.

The equation for the bent axis of a coil section with restrained ends at the moment when its stability is lost and after it has the form [2]

\[
y = \frac{f}{2}(1 - \cos \frac{2\pi x}{l}).
\]  

(1)

The result obtained from differentiation of function (1) is substituted in the equation for the bent axis length \( L \) at small sags; in this case, we can confine ourselves to the first two terms of the binomial series

\[
L = 2\int_0^\frac{1}{2} \left[ 1 + \frac{1}{2} \left( \frac{dy}{dx} \right)^2 \right] dx = l + \frac{f^2 \pi^2}{4l}. 
\]  

(2)

The change in the potential energy of load \( p \) when the coil section bends is described by the equation

\[
U_1 = p(L - l) = p\frac{f^2 \pi^2}{4l}. 
\]  

(3)

Now, the result from differentiation of function (1) is substituted in the energy equation for the bent coil section,

\[
U_2 = EJ\frac{1}{2} \int_0^\frac{1}{2} \left( \frac{d^2y}{dx^2} \right)^2 \, dx = EJ\frac{f^2 \pi^4}{l^3},
\]  

(4)

where \( E \) is the normal elasticity modulus of the metal, and \( J \) is the inertia moment of the coil cross-sectional area.

From the energy conservation law \( U_1 = U_2 \), we obtain the dependence for the axial component of the force compressing the coil section with the restrained ends,

\[
p = p_{cr} = \frac{4\pi^2 EJ}{l^2}.
\]  

(5)

The axial compression force \( p \) remains constant and equal to Euler’s critical value at the moment when the longitudinal stability is lost and during the subsequent sagging of the coil section. This conclusion is valid for small sags until the cross sections of the coil portion remain planar and normal with respect to the compression load.

According to Hooke’s law and Eq. (5), the section’s compression strain is given by

\[
\Delta l_c = \frac{4\pi^2 J}{Fl^2}.
\]  

(6)

In order to obtain a relation for the maximum sag of a heated coil section with restrained ends with the dis-