EXPERIMENTAL STUDY OF THE EFFECT OF TEMPERATURE AND STRESS ON THE MAGNETIZATION OF BOILER TUBES

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Results are presented from experiments conducted to determine the effect of thermal loads and local plastic deformation on the magnetization of heating surfaces.

Before the reliability of the water-wall system of steam generators can be improved, it will be necessary to develop a quick method of early detection of overheated and deformed tubes. Experience in the operation of drum-type boilers has shown that it is in the boiler tubes that defects of various types are found. Modern boilers have such highly developed heat-transfer surfaces that the overall length of the piping may be hundreds of kilometers. There are certain problems with the use of the commonly employed method of ultrasonic inspection (USI) to check the condition of boiler tubes. A nondestructive method of checking the quality of heating surfaces based on measurement of coercive force is one alternative to USI [1]. This method is based on the phenomenon, discovered in the 1970's, whereby boiler tubes become magnetized during service. Measurements have shown that for most steam-generator tubes the coercive force increases over the height of the furnace, similarly to the increase in local heat flux. One criterion of operational reliability is the inverse character of the change in coercive force over the height of the tubes. The use of this method at several heating plants yielded conflicting results: the points at which coercive force was measured often did not coincide with the locations of the defects; localization of the stressed sections was not always possible; some of the measurements could not be reproduced.

One variant of magnetic inspection is a method based on measurement of the magnetic field near the surfce of boiler tubes [2]. The advantages of this method of measuring magnetic properties are that it does not require special preparation of the surfaces to be inspected and does not introduce distortions into the magnetization. The latter in turn ensures that the results will be reproducible. The method is based on experimental data on the magnetization of steels 20 and 12Kh1MF under the influence of unidirectional elastic stresses. For example, in the case of the application and removal of elastic tensile and compressive stresses of 90 MPa in steel 12Kh1MF in a magnetizing field of 50 A/m, magnetic induction reaches 4 and 2 mT, respectively. It is conjectured that the most likely reason for the creation of stresses in the metal is loss of stability of the equilibrium of individual tubes in axial compression during service due to inadequate thermal compensation [3].

It was shown in [4] that boiler tubes are magnetized by thermoelectric currents which arise due to the difference in temperatures between the heated and back sides of the tubes. Magnetic induction increases with an increase in the thermal load and reaches 1.1 and 0.8 mT in tubes of steels 20 and 12Kh1MF with a temperature difference of 200°C.

The above-noted differences in the levels of magnetic induction of the steels being studied here make it possible to conclude that there is no definitive answer as to the reason for the magnetization of boiler tubes. Moreover, destabilization of the tubes due to inadequate thermal compensation can occur in the plastic as well as the elastic region. The distribution of tensile and compressive stresses over the height and about the perimeter of the tubes will be nonuniform and will depend on the compressive force and the moment in the stiff zone. The stresses in the region of maximum deflection of the tubes may exceed the yield point even if instability begins at compressive stresses corresponding to the elastic region. It is known (see [5], for example) that the magnetization of metals depends on the stresses and the temperature. Detailed studies have been made of the effect of unidirectional compressive and tensile stresses and stresses from a turning moment on magnetiza-

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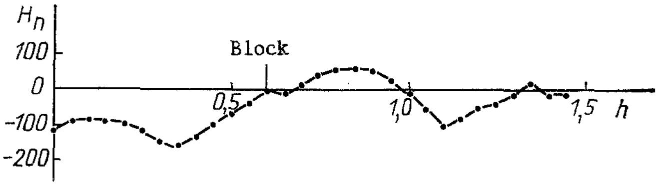

Fig. 1. Distribution of magnetic-field strength on the heated side of tube No. 76 in the right lateral water wall of the TGM-96 boiler in Heat-and-Power-Plant No. 8 of Mosenergo. H_n, A/m; h, m.

tion. There is no information on magnetization in the case of tube destabilization with the formation of elastic and plastic strain regions. Boiler tubes in the as-received condition generally have high internal stresses. Since the theoretical temperature of the tubes in steam generators during service reaches 400°C, we should expect a decrease in their internal stresses and an interest in magnetization.

In 1988, we inspected the water-wall system of the steam generators at several heating and power plants under the administration of Mosenergro (Moscow Regional Administration of Power System Management). We found several magnetized tubes. Figure 1 shows the typical distribution of the normal component of magnetic field on the heated side of one such tube after the boiler was shut down (to be more precise, here and below we show the distribution of the normal component of magnetic induction near the surface of a body magnetized in the Earth's magnetic field; this inconsistency has to do with the fact that the measurements were made with the use of a ferroprobe magnetometer designed to measure magnetic-field strength and having a scale in A/m). The tube had an outside diameter of 60 mm and a wall thickness of 6 mm. The material of the tube was steel 20. Measurements of the magnetic induction of individual cut tubes showed values ranging up to 30 mT. This result does not correlate with the test data in [2, 4].

The creation of a magnetic method for early detection of overheated and deformed tubes is possible only after determination of the connection between the magnetization of the metal and the temperature and stresses which develop in the tubes during loss of stability. To determine this relationship, we built a special experimental unit. The working section was a steel-20 tube in the condition received. The tube had outside and inside diameters of 13.88 and 8.35 mm and a length of 1.5 m. The working section was placed on a No. 12 channel in the vertical position. The section rested in specially designed stainless steel supports simulating the conditions of attachment of the water-wall tubes in the boiler. While studying the relationship between the magnetization of the metal and temperature, we turned the lock nuts in the supports so as to allow for free thermal expansion. In tests conducted with tubes under conditions simulating loss of stability, we tightened the nuts to provide a rigid fastening. The tube used in each test was heated uniformly about its perimeter by radiant heat from external and internal heaters made of nichrome wire. An alternating current was passed through the wire. Only part of the working section was heated during operation of the external heater, while the entire working section was heated when the internal heater was turned on. We measured the magnetic fields of the heaters when the maximum current was passed through them. The strength of the fields did not exceed 3 A/m, i.e., the fields were much weaker than the Earth's field. To reduce heat loss to the environment, the working section was insulated with 10-mm-thick asbestos cord. In the tests which involved local heating, spiral copper tubes were positioned 0.5 and 1.0 m from the ends of the tube and water with a temperature of 20°C was directed through them. These spirals removed the heat supplied to the working section without allowing it to propagate by conduction to the unheated part.

The temperature of the tube was measured with chromel—alumel thermocouples positioned in eight different sections. The thermocoules were attached to the surface with an organo-silicate adhesive having a high thermal conductivity. The deviation of the working section from its initial state upon loss of stability was determined at the middle of the tube with a marking gauge. The strength of the magnetic field near the tube surface was measured with a digital ferroprobe magnetometer specially designed for the conditions in the boiler. The ferroprobe was made of a strip of permalloy 79NM. The strip was 6 mm long, 2 mm wide, and 0.05 mm thick. The magnetometer had the following specifications: range of measurable

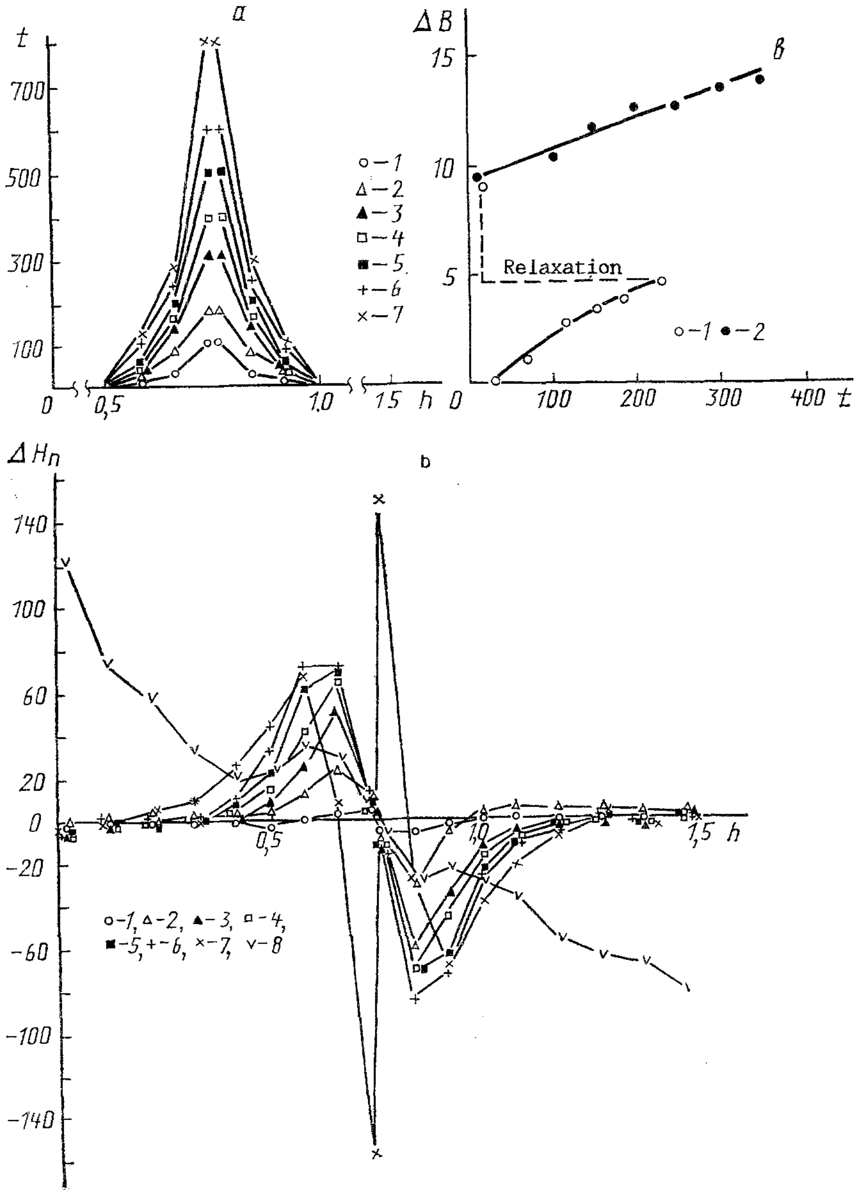

Fig. 2. Distributions of temperature and the magnetic parameters of a tube with a change in the thermal load: a) regimes of the temperature state; b) relative strength of the magnetic field; 1-7) data corresponding to the temperature distributions in Fig. 2a; 8) relaxation; c) magnetic induction; local heating; 2) general heating. ΔB, mT; t, °C.

fields 0.5-2·10³ A/m; distance between the ferroprobe and the tube surface 1.1 mm for measurement of the tangential component and 5.5 mm for measurement of the normal component; measurement error no smaller than 4%.

In ferromagnetic materials such as steel 20, the location of the boundaries between the domains and the orientation of the vectors of spontaneous magnetization in them are determined by the condition of the free-energy minimu. Here, the free energy is composed of the energy of the internal stresses, the energy of the external stresses, and the energy of the external field (in our tests, the latter was the energy of the Earth's magnetic field). In the absence of external stresses, for steel with high internal stresses the transition to a new state is made by annealing. This transitional process can be of two types: recovery, and recrystallization. For steel 20, recovery – during which only some of the internal stresses are relieved – occurs up to temperatures of about 400°C. At higher temperatures, recrystallization begins with the growth of new grains. In the temperature region above 768°C, the steel loses its magnetic properties. During boiler operation, the temperature of water walls made of steel 20 reaches 400°C. This temperature may also be exceeded under abnormal conditions connected with thermal fluctuations, disruptions in circulation, etc.

To determine the connection between the temperature of the water walls and magnetization, experiments were conducted under conditions providing for local and general heating of the working section.

The distribution of temperature and the normal component of magnetic-field strength over the height of the working section in the case of local heating is illustrated by Fig. 2a and 2b. In regimes 1-6, the measurements were made in both the hot and cold states after removal of the thermal load. In regime 7, the strength of the field was measured in the hot state when the surface temperature reached 800°C. The base data was the magnetic field of the tube in the condition in which it was received. It is evident that an increase in thermal load is accompanied by magnetization of the tube. The maximum change in field strength is seen on the unheated section. The field strengths in regimes 1-6, measured with the tube in the hot and cold states, were nearly constant. In regime 7, the difference in the magnetic field for these states was substantial. This result can be explained by the fact that the temperature of the steel exceeded the Curie point, where the domain structure is destroyed. The increase in field strength seen in regime 8 seven days after the completion of tests involving local heating (Fig. 2b) is evidently due to a delay in the reduction of the internal stresses throughout the tube, i.e., their relaxation. This phenomenon must be considered when developing a method for detecting overheated boiler-tube sections in which the external stresses are no greater than the yield point. We attempted to study the change in the magnetic properties of steel 20 during thermal cycling. Repeated temperature cycles involving heating and cooling and following continuously after one another had almost no effect on the magnetic field of the working section.

The determination of the magnetic properties by measuring the strength of the magnetic field near the tube surface is based on the principle of the continuity of the tangential component H_τ of field strength and the normal component B_n of the induction of the field at the boundary between two media. Since the following holds at a metal-air boundary

$$B_n = \mu_0 H_n, \tag{1}$$

where μ_0 is the magnetic constant and H_n is the empirically measured normal component of magnetic-field strength, the magnetic induction of a tube with external and internal radii r_2 and r_1 and height h was determined from the equation

$$\int_{r_1}^{r^2} \Delta B_\tau r dr + \mu_0 r_2 \int_0^{h/2} \Delta H_n dz = 0. \tag{2}$$

The results of our analysis of the test data are shown in Fig. 2c. Also shown in the figure are the results of experiments conducted with general heating of the working section. We used the mean-integral temperature of the working section in the tests conducted with local heating. In the latter case, the magnetic induction of the tube increases and reaches 5 mT, and relaxation of the internal stresses results in magnetization of the entire tube to 9 mT. In the case of general heating, induction also increases and reaches 14 mT at a temperature of 350°C. The empirical data confirmed that one reason for the high degree of magnetization of boiler tubes is a reduction in internal stresses due to thermal loading.

To determine the contribution of the external stresses to magnetization, we conducted experiments with a fastened tube undergoing loss of stability due to heating. Calculations performed for the working section in accordance with Euler's method showed that the section should have become unstable when heated 25°C, while in the elastic strain region. Since the tube was not completely rigid after fastening, we began the experiments with a temperature of 100°C. Figure 3a shows the distribution of the normal component of magnetic-field strength over the height of the working section. The base data was the magnetic field of the tube after the end of the experiments with just a thermal load. The measurements were made in the cold state after the tube was heated to the working temperature. It is apparent that the field changes little up to 150°C, while its strength increases sharply at higher temperatures. An increase in the temperature of the working section is accompanied by an increase in the residual deflection, indicating the development of plastic strain at the middle of the tube. It should be noted that the distributions of field strength over four working-section generatrices 90° apart were the same in each regime and did not depend on the external stresses over the tube height and perimeter. The greater magnetization during cooling is evident from a comparison of the measurements of the field in the hot (not shown

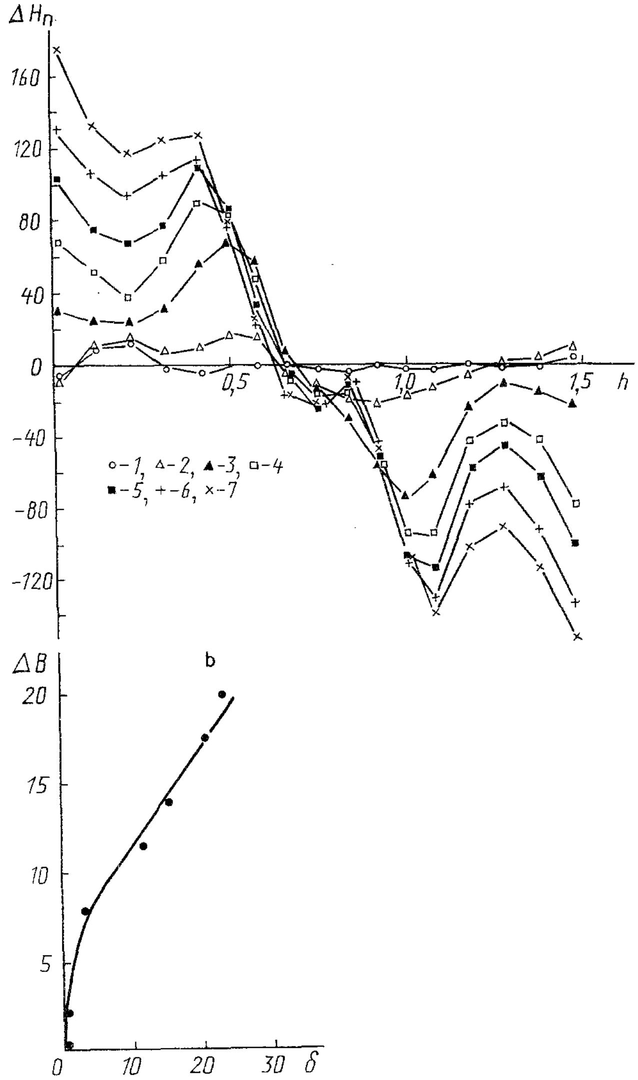

Fig. 3. Change in the magnetic properties of a tube during loss of stability: a) strength of magnetic field; 1) t = 100°C, δ = 0.1 mm; 2) 150 and 0.4; 3) 200 and 3.2; 4) 250 and 11.2; 5) 300 and 15.7; 6) 350 and 20.7; 7) 375 and 23.1; b) magnetic induction, δ, mm.

in the figure) and cold states. This result is connected with the fact that when the working section is locally heated beyond the yield point, its unloading is accompanied by tensile elastic stresses. These stresses increase the magnetization of metals with positive magnetostriction. No changes were seen in the magnetic properties of the deformed tube over time.

Figure 3b shows the change in the magnetic induction of the tube in relation to the residual deflection. The calculations were performed with Eq. (2). Induction increases with deformation and reaches 20 mT with a residual deflection of 23 mm. The contributions of temperature and external stresss to the magnetization of the tube in the case of loss of stability are roughly the same.

Thus, the high level of magnetization of boiler tubes is due to thermal loading, local plastic deformation occurring during loss of stability resulting from inadequate thermal compensation, and tensile stresses which develop in the tubes during cooling. These results can be used to devise a quick method for early detection of overheated and deformed surfaces.

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MOTION OF A GAS IN A CYCLONE HEAT EXCHANGER

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A semi-empirical theory of turbulence is used to obtain relations for calculation of the field of gas velocity in the flow core and boundary layer in a cyclone chamber. To close the system of Navier–Stokes equations, the apparent shear stress is represented in the form of the gradient dependence in circulation. The relations for calculating the tangential component of velocity were derived using experimental data on the qualitative character of the distribution of apparent shear stress over the radius of the cyclone.

In order to devise methods of calculating heat- and mass-transfer processes between a gas and particles in cyclone heat exchangers, it is necessary to thoroughly examine the aerodynamic structure of the twisted disperse flow – including the velocity field of the gas in the cyclone. Most investigations of the aerodynamics of cyclone chambers have been experimental studies of the distribution of the components of gas velocity in the core of the flow. Different empirical relations have been proposed for calculation mainly of the tangential component of velocity. There has been little study of the boundary-layer gas flow in cyclones, even though the dispersed material moves mainly in this region in cyclone chambers with "dry" walls. In the present study, we attempt to use a semi-empirical theory of turbulence to obtain relations for calculating the velocity field of the gas flow throughout the volume of a cyclone chamber.

We will represent the running parameters of the flow as consisting of the time-averaged radial u, axial w, and tangential v components of velocity and the fluctuation components u', w', v'. Then the Navier–Stokes equations are augmented by expressions for the Reynolds stresses. We will write this equation in cylindrical coordinates in the tangential direction, taking into account the symmetry of the twisted flow relative to the axis of the cyclone:

$$u\frac{\partial v}{\partial r}+w\frac{\partial v}{\partial x}+\frac{vu}{r}=\nu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial vr}{\partial r}\right)+\frac{\partial^2 v}{\partial x^2}\right]+\frac{1}{\rho}\left[\frac{\partial\tau_{r\varphi}}{\partial r}+\frac{2}{r}\tau_{r\varphi}+\frac{\partial\tau_{x\varphi}}{\partial x}\right], \tag{1}$$

where $\tau_{r\varphi} = -\rho u'v'$, $\tau_x = -\rho v'w'$ are components of the turbulent shear stress.

Here, the continuity equation will have the form

$$\frac{1}{r}\frac{\partial ur}{\partial r}+\frac{\partial w}{\partial x}=0. \tag{2}$$

To close the system of Navier–Stokes equations in the theory of turbulent motion [1], empirical relations are introduced to link the apparent shear stress with the time-averaged velocities. For $\tau_{r\varphi}$, this connection is usually expressed by one of two methods:

1) by generalization of the Karman similarity hypothesis to curvilinear flows

$$\tau_{r\varphi}=\rho\nu_t r\frac{d}{dr}\left(\frac{v}{r}\right); \tag{3}$$

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