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Marine Boiler Tubes Spotting Impact on Its Operation Parameters: a Case Study

V. Protsenko[1,*], M. Babii[2], V. Nastasenko[3]

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ABSTRACT

Article deals with ship power engineering, namely with ship steam boiler operation parameters and fuel efficiency. Boiler Aalborg MISSION OL tubes surface scale and soot contamination impact on tubes stress state and operation parameters studied in the article. It is shown that scale contamination on the inner surface of the tubes is the cause of their overheating. Wall temperature difference increase from 10°C to 145°C leads increase in the equivalent stress up to 10 times. Scale formation on tube wall increases thermal resistance and became a reason of specific heat flow reduce by 12.7%, which leads to a diminution in the steam productivity of the boiler from 25000 to almost 21000 kg/h and exhaust gas temperature growth by almost 250°C. The case presented in article is successfully reviewed by the authors in the educational process in the academic disciplines "Basics of Ship Power Engineering" and "Ship Boiler Plants".

1. Introduction.

Modern ship power engineering has one of the target functions of ensuring the minimization of operating costs, among which a significant percentage is occupied by the costs of fuel, operation, and repair of equipment [1, 2]. A high degree of automation of energy equipment does not guarantee absolute control and safety of its operation [3], therefore, control of operational safety directly depends on the qualification of the crew, which is ensured by the quality of its training, which is significantly increased when using case study [4]. Boilers on a modern ship are one of the most complex and important energy-generating elements, which combine great energy potential and significant danger for the engine crew, cargo, and the ship.

The safe operation of boilers should be based on solid knowledge of the processes that occur with the boiler and its elements over time, the mutual influence of these processes, and based on this knowledge, the implementation of risk management and decision-making during the operation of boilers. Literature on boilers [5, 6] distributed for the training of marine engineers often provides a description of their operation and the occurrence of damage in an abstract manner, without a detailed disclosure of the interaction of energy generation and transmission processes with the mechanism of failures that occur in operation and their consequences. Particularly, the influence of contamination of the heating surfaces of boilers (Fig. 1, Fig. 2) on the destruction of their elements (Fig. 3) and the change in operational indicators is not described enough.

This work aims to reveal the influence of contamination of the heating surfaces of ship steam boilers on the strength indicators of their tubes (and therefore safety parameters), the economy of operation (fuel consumption) on a specific example of a modern boiler for use in the training of future ship mechanics in the case study process.

[1]Doctor of Technical Sciences, Professor of the Department of Transport systems and technical service of Kherson National Technical University, Ukraine. Tel. (+380) 504947472. ORCID ID: 0000-0002-3468-4952. E-mail Address: eseu@ukr.net.

[2]Ph.D. Associate Professor of the Department of Operation of Ship Power Plants of Kherson State Maritime Academy, Ukraine. Tel. (+380) 990259540. ORCID ID: 0000-0002-0560-2081. E-mail Address: m_babiy@ukr.net.

[3]Doctor of Technical Sciences, Professor of the Department of Transport Technologies and Mechanical Engineering of Kherson State Maritime Academy, Ukraine. Tel. (+380) 953005804. ORCID ID: 0000-0002-0330-1138. E-mail Address: nastasenko2004@ukr.net.

*Corresponding author: V. Protsenko. E-mail Address: eseu@ukr.net.

Figure 1: Tubes with internal wall covered with scale.

Source: [9].

Figure 2: Tubes with external walls covered with soot.

Source: [10].

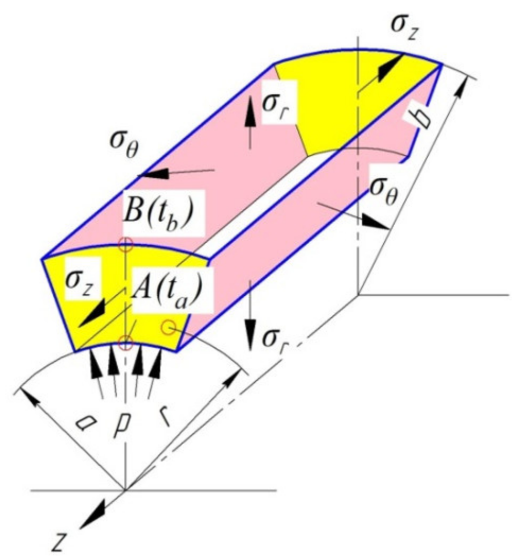
Figure 3: Tube broken through overheating.

Source: [11].

2. Presentation of the main material.

During the operation of a water-tube boiler, a three - dimensional stress state [7, 8] (Fig. 4) occurs in the material of the tube walls, namely total radial , circumferential, and axial stresses (1), the occurrence of which is the result of loading the tubes with internal pressure p and temperature difference $\Delta t = t_a - t_b$ (t_b is the temperature of the outer surface of the wall (gas side), t_a is the temperature of the inner surface of the wall (steam side)).

Figure 4: Tube stressed state diagram.



Source: Authors.

$$\begin{cases} \sigma_r = \sigma_{rp} + \sigma_{rt}\,; \\ \sigma_\theta = \sigma_{\theta p} + \sigma_{\theta t}\,; \\ \sigma_z = \sigma_{zp} + \sigma_{zt}\,. \end{cases} \qquad (1)$$

When the equivalent stress according to Huber-Mises (2) [12, 13] reaches the yield point of the tube material σ_y, a crack begins to appear in its wall, which leads to the destruction of the tube and poses a danger.

$$\sigma_e = \sqrt{0.5\left[(\sigma_\theta - \sigma_z)^2 + (\sigma_z - \sigma_r)^2 + (\sigma_r - \sigma_\theta)^2\right]} \leq \sigma_y \qquad (2)$$

Stresses from steam pressure are calculated by expressions (3), and from temperature difference by (4)

$$\begin{cases} \sigma_{rp} = p\,\dfrac{a^2}{b^2 - a^2}\left(1 - \dfrac{b^2}{r^2}\right); \\ \sigma_{\theta p} = p\,\dfrac{a^2}{b^2 - a^2}\left(1 + \dfrac{b^2}{r^2}\right); \\ \sigma_{zp} = 0 \quad \text{(tube open);} \end{cases} \qquad (3)$$

$$\begin{cases} \sigma_{rt} = \dfrac{E\alpha\chi}{2(1-\mu)} \times \dfrac{b^2 \ln \dfrac{b}{r} + a^2 \ln \dfrac{r}{a} - \left(\dfrac{ab}{r}\right)^2 \ln \dfrac{b}{a}}{b^2 - a^2}; \\ \sigma_{\theta t} = \dfrac{E\alpha\chi}{2(1-\mu)} \times \dfrac{b^2 \ln \dfrac{b}{r} + a^2 \ln \dfrac{r}{a} + \left(\dfrac{ab}{r}\right)^2 \ln \dfrac{b}{a} - (b^2 - a^2)}{b^2 - a^2}; \\ \sigma_{zt} = \dfrac{E\alpha\chi}{1-\mu} \times \dfrac{b^2 \ln \dfrac{b}{r} + a^2 \ln \dfrac{r}{a} - \dfrac{b^2 - a^2}{2}}{b^2 - a^2}, \end{cases} \quad (4)$$

where:
$a = 0{,}5d_{int}$ – tube internal radius;
$b = 0{,}5d_{ext}$ – tube external radius;
r – radial coordinate of tube wall point, where stresses are calculated;
E = 210000 MPa – steel elasticity modulus;
μ = 0,3 – Poisson's ratio of steel;
α = 0,000012 °C^{-1} – steel linear expansion coefficient;
$\chi = \frac{\Delta t}{\ln \frac{b}{a}}$ – temperature effort.

To find the temperature of the walls t_b and t_a, we will use the basic equation of heat transfer, which relates the specific heat flow q with the state of the wall and the temperatures of the media between which heat transfer occurs.

$$q = K(t_g - t_s) \quad (5)$$

where:
K – heat transfer coefficient from gases to steam;
t_g – gases temperature;
t_s – steam temperature.

$$K = \left[\frac{1}{\alpha_{gv}} + \frac{\delta_{st}}{\lambda_{st}} + \frac{\delta_w}{\lambda_w} + \frac{\delta_{sc}}{\lambda_{sc}} + \frac{1}{\alpha_{ws}}\right]^{-1} \quad (6)$$

where:
α_{gw}– gases to wall heat exchange coefficient;
α_{ws}– wall to water-steam mixture heat exchange coefficient;
δ_{st} and λ_{st}– soot thickness and thermal conductivity coefficient;
$\delta_w = b-a$ and λ_w– wall tube thickness and material thermal conductivity coefficient;
δ_{sc} and λ_{sc}– scale thickness and thermal conductivity coefficient.

Wall temperatures are determined from the Newton-Richmann law equation

$$\begin{aligned} t_b &= t_g - q\alpha_{gw} \\ t_a &= t_s + q\alpha_{ws} \end{aligned} \quad (7)$$

Steam generation power will be

$$Q_s = qA = D_s(V_s - c_{fw}t_{fw}) \quad (8)$$

where:
$A = \pi n d_{ext} L$ – heat transfer surface area;
n – boiler tubes number;
L – tubes length;
D_s – boiler steam productivity;
i_s – steam enthalpy;
c_{fw} – feed water heat capacity;
t_{fw} – feed water temperature.

As a result of contamination of the surface of the tubes, the specific heat flow q will decrease, which, with an unchanged fuel supply to the boiler fuel consumption G_f, will lead to a decrease in the steam productivity of the boiler D_s according to the expression (9) and an increase in the temperature of the exhaust gases to the value (10) [14].

$$Q_s = \frac{3600qA}{(V_s - c_{fw}t_{fw})} \quad (9)$$

$$t_{eg} = \frac{Q_f^l + c_f t_f + 14,3\alpha c_a t_a - \frac{3600qA}{G_f}}{(14,3\alpha + 1)\, A_{eg}} \quad (10)$$

where:
i_s – steam enthalpy;
c_{fw} – air heat capacity;
t_{fw} – air temperature;
Q_f^l – fuel lower heat of combustion (calorific value);
Q_f – fuel heat capacity;
t_f – fuel temperature;
α – air excess coefficient;
c_a – air heat capacity;
t_a – air temperature;
c_{eg} – exhaust gases heat capacity.

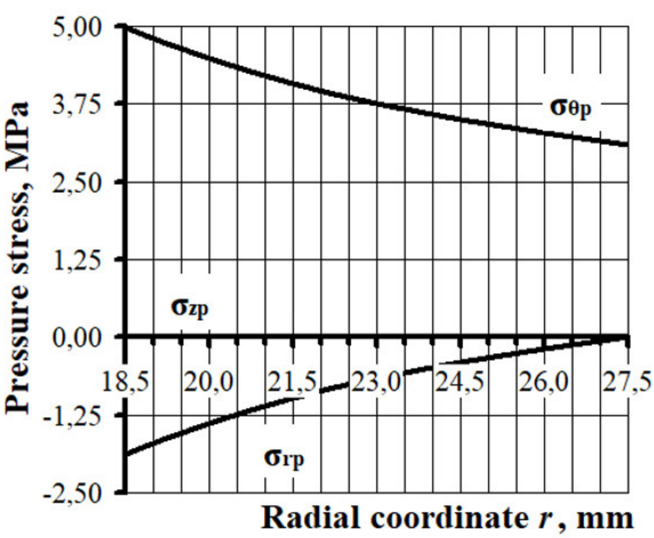
3. Results and discussion.

We will evaluate the influence of the sediments (scale and soot) thickness on the parameters of the boiler using the example of the Aalborg MISSION OL model 25000 with steam productivity D$_s$ = 25 t/h, maximum pressure p = 1,8 MPa (enthalpy i_s = 2792.2 kJ/kg, temperature t_s = 204 °C). Lifting pipes (n = 395 pcs) have a diameter d_{ext}/d_{int} = 55/37,4 mm and a length L = 4505 mm. The temperature of the gases washing the tubes t_g = 1100 °C. Feed water temperature t_{fw} = 70 ºC; feed water heat capacity c_{fw} = 4.2 kJ/(kgºC); fuel temperature t_f = 120 ºC; fuel heat capacity c_f = 2,039 kJ/(kgºC); air temperature t_a = 45 ºC; air heat capacity c_a = 1,009 kJ/(kgºC); exhaust gas temperature t_{eg} = 420 ºC; exhaust gases heat capacity c_{eg} = 1,16 kJ/kgºC; excess coefficient of air α = 1,15; lower heat of combustion of fuel Q_f^l= 40200 kJ/kg (for RMG 180 fuel). We assume that the pipes are made of ASTM A210 type steel with yield point stress σy = 275 MPa, heat exchange coefficients: α_{gw} = 65 W/(m^2°C), α_{ws} = 4000 W/(m^2°C), thermal conductivity coefficients of soot and scale λ_{st} = 0,35 W /(m°C), λ_{sc} = 3,5 W/(m°C) [15, 16].

The calculation results are presented in Fig. 5...Fig. 12 testify to the following. Data on the intensity of the total stresses from the temperature difference and steam pressure (Fig. 7), as well as the equivalent stresses (2) (Fig. 8) along the radius of the tube, demonstrate that the most stressed points are points A (Fig. 4) on the inner surface tubes (r = 18,7 mm), where the formation of a crack will begin, since tensile stresses (positive) act here. On the outer surface of the tube (point *B*) there are compressive stresses (negative). Thus, point *A* on the inner surface of the tubes will be considered the most dangerous point. Thermal stresses have the greatest influence on the stressed state of the tubes at point *A* (Fig. 5 and Fig. 6). Thus, the circumferential stresses from the temperature difference ($\sigma_{\theta t} = 21,4MPa$) are more than 4 times higher than the circumferential stresses from the steam pressure ($\sigma_{\theta p} = 5,0MPa$), the axial stresses from the temperature difference are $\sigma_{zt} = 21,2MPa$ opposite to the zero stresses ($\sigma_{zp} = 0$) from the steam pressure.

The presence of scale on the inner surface of the tubes leads to an increase in temperature difference Δt (Fig. 9) for the increase in temperature t_b point *B* on the outer surface of the tube wall. Thus, with an increase in scale thickness from 0 to 8 mm, the temperature t_b increases by 58% - from 231 °C to 364 °C, and the temperature difference Δt is lower 14 times - from 10 °C to 145 °C, this leads equivalent stresses increase 10 times (Fig. 10) – from 26,3 MPa to 267,2 MPa. Scale thickness δ_{sc} growth up to 8 mm can lead to the formation of a crack in the tube station (σ_y = 275 MPa) with the onset of rupture (Fig. 3). As can be seen from the graph in Fig. 10, a similar effect, coverage the surface of the tubes with soot less than 1 mm thick.

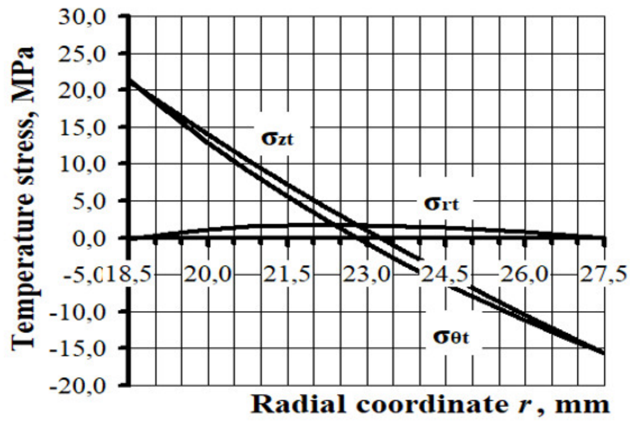
Figure 5: Dependence of steam pressure generated stress on tube wall point radial coordinate.



Source: Authors.

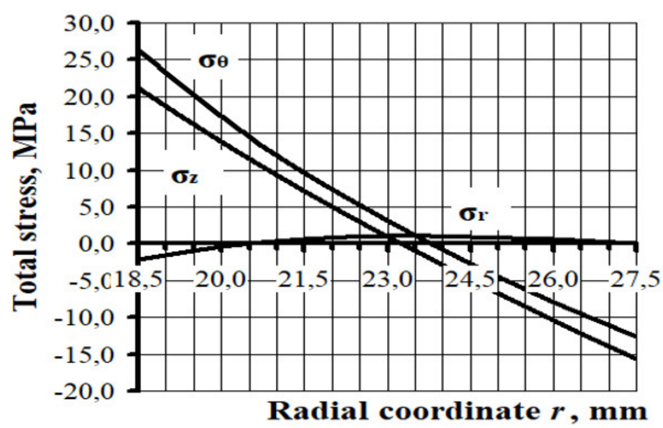
With increased scale thickness δ_{sc} from 0 to 8 mm, the thermal support should be increased until the specific heat flow *q* decreases by 12,7% - from 56,5 kW/m^2 to 49,3 kW/m^2 (Fig. 11), which causes a decrease in steam productivity D_s by 15% – from 25,000 kg/h to 21,171 kg/h (Fig. 12) and an increase in the temperature t_{eg} of processed gases by up to 250 °C – from 420 °C to 668 °C (Fig. 13). Increasing steam productivity at the nominal level will require an increase in fuel consumption by ΔG_f = 345,6 kg/h (Fig. 14), which is confirmed by data from Alfa-Laval [17].

Figure 6: Dependence of temperature difference generated stress on tube wall point radial coordinate.



Source: Authors.

Figure 7: Dependence of total stress on tube wall point radial coordinate.



Source: Authors.

Figure 8: Dependence of equivalent stress on tube wall point radial coordinate.

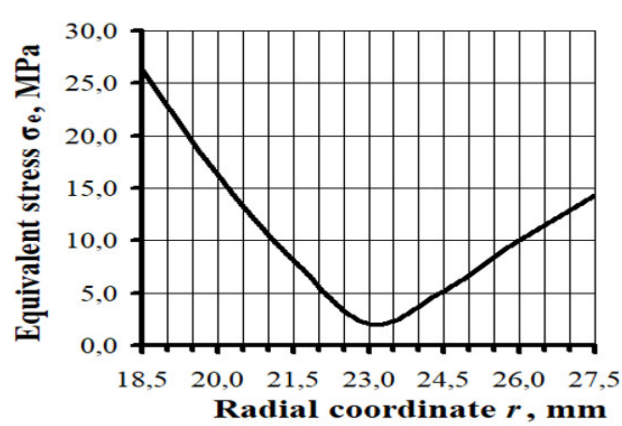


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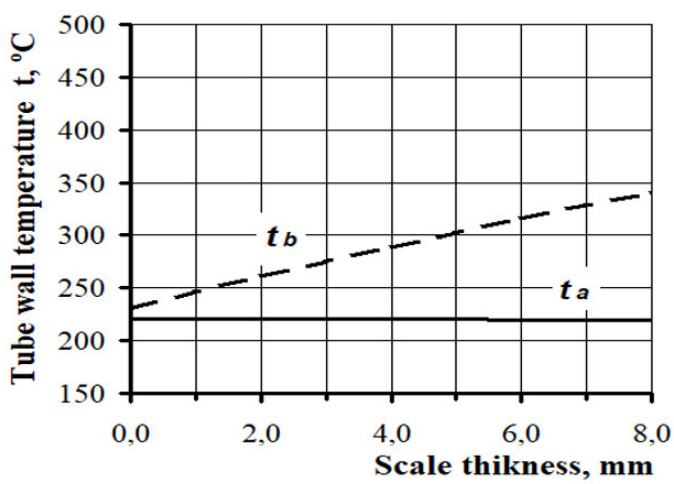
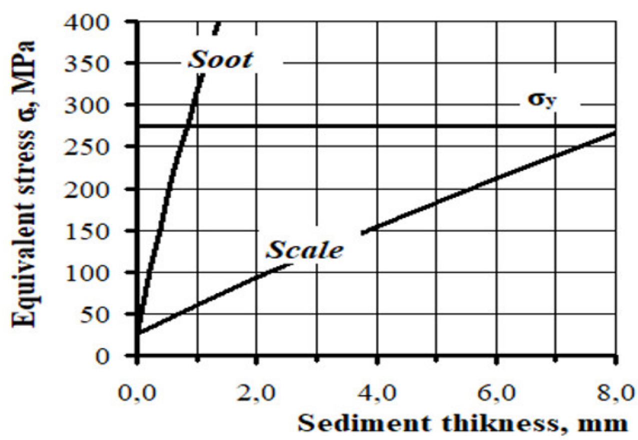
Figure 9: Dependence of tube wall external and internal point temperature on scale thickness.



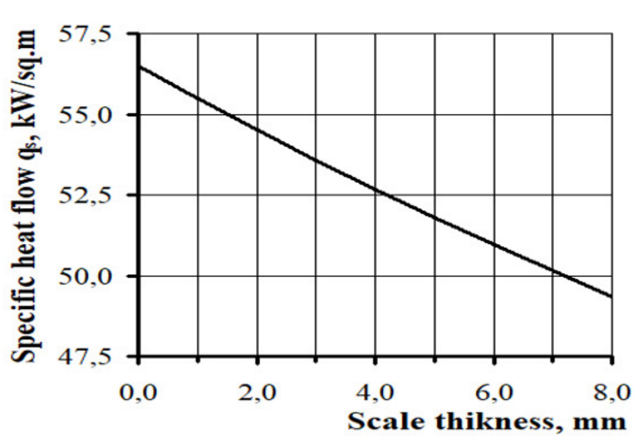
Source: Authors.

Figure 10: Dependence of tube wall internal point equivalent stress on sediment thickness.



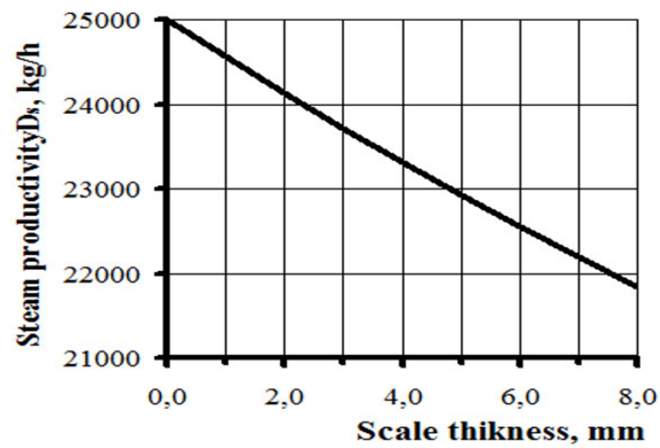
Source: Authors.

Figure 11: Dependence of specific heat flow on scale thickness.



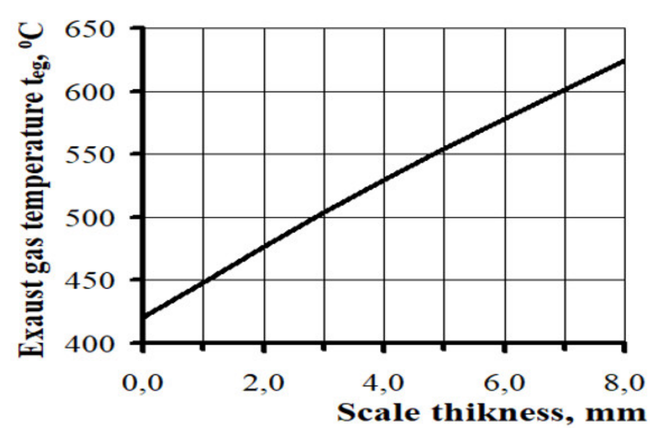
Source: Authors.

Figure 12: Dependence of boiler steam productivity on scale thickness.



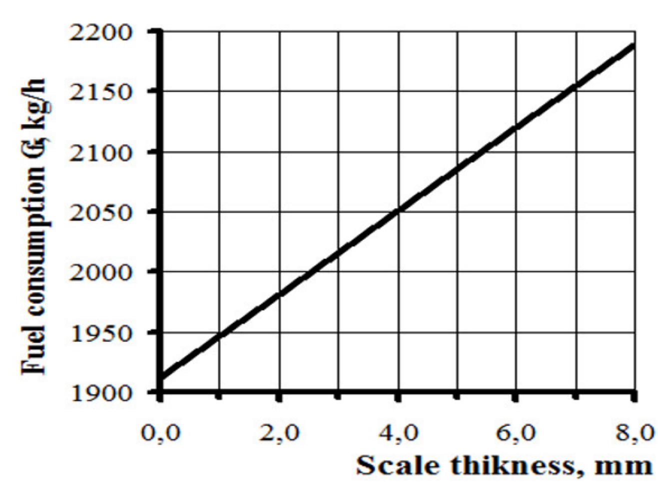
Source: Authors.

Figure 13: Dependence of boiler exhaust gases temperature on scale thickness.



Source: Authors.

Figure 14: Dependence of boiler hour fuel consumption on scale thickness.



Source: Authors.

Conclusions.

1. Based on the basic conditions of heat transfer and support of materials, the contamination on the surface of the steam boiler tubes on their walls stresses is shown on the example of the marine water-tube steam boiler Aalborg MISSION OL. The case is successfully reviewed by the authors in the educational process in the academic disciplines "Basics of Ship Power Engineering" and "Ship Boiler Plants".
2. It is shown that there is a constant pressure on the surface of the tubes, the predominant impact on the stress in the tubes is the temperature difference, and the most stressed zone is the inner (cold) surface of the tubes, which is washed with water, and there is a crack formation begins when the tubes overheat due to scale thickness growth. It was revealed that circumferential stresses from the temperature difference are more than 4 times higher than the circumferential stresses from the steam pressure.
3. The formation of scale on the inner surface of the tubes is the cause of their overheating - with increased scale thickness δ_{sc} from 0 to 8 mm, the wall temperature difference Δt increases over 14 times - from 10 °C to 145 °C.
4. Overheating of the tube walls will result in an increase in the equivalent stress by up to 10 times. It is shown that a scale of 8 mm can reach the core by forming a crack in the tube station, the fragments at which equivalent stress ($\sigma_?$ = 267,2 MPa) reach practically the yield limit of the tube material (σ_y = 275 MPa). A similar effect can be achieved by obstructing the surface of the tubes with soot less than 1 mm in thickness.
5. It has been shown that the formation of scale on the tubes with a thickness of 8 mm for the expansion of the thermal support reduces the specific heat flow q by 12,7%, which leads to wastage in the steam productivity of the boiler D_s by 3829 kg/h and an increase in the exhaust gas temperature t_{eg} almost at 250 °C.
6. Increasing the steam productivity of the boiler to the nominal level due to the presence of the indicated tubes contamination with scale will require a growth in fuel consumption by ΔG_f = 345,6 kg/h.
7. The results of the investigation made it possible to enhance by future ship mechanics the importance of processes that are carried out with the boiler and its elements in time, the mutual flow of these processes, and changes in boilers operating parameters initiated by the tubes surface contamination.

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