Розроблена методика розрахункової оцінки впливу локальної нерівномірності теплових потоків на пошкоджуваність та залишковий ресурс елементів енергетичного устаткування. Коректність методики доведено чисельними дослідженнями теплового, напружено-деформованого стану та залишкового ресурсу трубопроводів котлоагрегатів. Метою розробки є подовження терміну експлуатації енергетичного обладнання

Ключові слова: котельний агрегат, напружено-деформований стан, малоциклова утомленість, пошкоджуваність, залишковий ресурс

Разработана методика расчетной оценки воздействия локальной неравномерности тепловых потоков на повреждаемость и остаточный ресурс элементов энергетического оборудования. Корректность методики доказана многочисленными исследованиями теплового, напряженно-деформированного состояния и остаточного ресурса трубопроводов котлоагрегатов. Целью разработки является продление срока эксплуатации энергетического оборудования

Ключевые слова: котельный агрегат, напряженно-деформированное состояние, малоцикловая усталость, повреждаемость, остаточный ресурс

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ANALYSIS OF RESIDUAL OPERATIONAL RESOURCE OF HIGH-TEMPERATURE ELEMENTS IN POWER AND INDUSTRIAL EQUIPMENT

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1. Introduction

Energy sector in Ukraine employs a significant number of energy and industrial boilers of different capacity, furnaces, driers, gas-turbine plants, etc., which exhausted their operational life cycle. Work experience of such installations demonstrates that one of the essential factors that worsen reliability and efficiency is the non-uniform character of fuel distribution in combustion chamber, both in space and over time [1]. This leads to the violation of temperature and thermal-hydraulic modes of heating surfaces, occurrence of additional thermocyclic loads on metal and, eventually, to installation's breakdown.

A violation of the optimum ratio "fuel-air" in separate burners and in the combustion chamber as a whole causes excessive chemical and mechanical incompleteness of fuel combustion, as well as nitrogen oxides emissions larger than those permitted by the European regulations [2, 3].

2. Literature review and problem statement

One of the main elements of fire-technical systems whose characteristics largely influence their effectiveness, efficiency, operation lifecycle, formation of heat flows in the combustion space, emissions of nitrogen oxides, etc., is a burner device. At present, energy sector and industry employ mostly burner devices of the register type. When using register burners, a deviation in the temperature profile of gases is almost always observed and, accordingly, the magnitude of stress in the elements, from the calculated values.

For the water heating boilers DKVR-20-13 (Biysk Boiler Building Plant, Russia), the causes of emergency stops are as follows:

– burnout of pipes in front screen – 45 %;
– deformations and breakups in side screens – 37 %;
– burnout of superheaters – 7 %;
– damage in walling, cladding, casing – 4 %.

That is, more than 80 % of emergency stops of the boiler are related to the overheating of screen pipes [4].

Conducted measurements of temperature of gases in the furnaces of pulverized coal boilers P-49 and P-57 [5] revealed that the unevenness of temperature field may reach (400–500) °C. In addition, the difference in the values of mean integral temperatures of gases along the cross section of furnace under constant operation mode can be up to (300–350) °C. It was found during tests that under a constant mode of work, in certain intervals of (5–10 min), considerable gas temperature fluctuations occur in the same cross-sections of the furnace.

Cyclic local non-uniformities of temperature lead to the emergence of thermal stresses in different elements of equipment: couplings of water heating water pipe boilers [6], blades of gas turbines [7], drums of boilers of various purpose [8, 9], etc. In addition, for example, in hot water boilers [10], characteristics of heat exchange are influenced by the heat carrier quality. In power boilers, one should take into consideration external and internal corrosion of metal [11]. Reliability of equipment performance is also affected by such factors as instability and torch pulsations [12]. One of the most dangerous elements of pipeline system is the bends in pipes [13].

One of the most severe regimes from the point of view of additional thermal stresses is a heatstroke. It occurs in the case of heating cold pipeline with hot gases or when cooling a hot pipeline by cold water. A heatstroke typically happens in the beginning of starting modes. At heatstroke, the metal wall of the pipeline experiences significant strains, which are several times larger than the estimated ones.

In some cases, the unevenness of temperature field leads to lowering the temperature of gases due to an increase in the coefficient of excess air or through feeding part of combustion products to the burner for recirculation [14].

One of the possible ways to maximize efficiency of the combustion process and formation of the required temperature profile may include the application of technology of micro-torch burning of fuel (gas) in burners of the stabilizing type [15]. The indicated technology is based on the results of studies performed at the NTUU "Kyiv Polytechnic Institute named after Igor Sikorsky" (Ukraine).

The issues of change in the gas-dynamic and thermal characteristics at fuel burning by stabilizers were examined in article [16]. Peculiarities of the flow of gases, mixture formation of fuel with oxidant are addressed in paper [17].

In the contemporary literature, there is a lack of materials on the comprehensive approach to solving a problem about the impact of gas dynamics and heat exchange on the thermally stressed state of high-temperature elements using computer simulation.

Diagnosing a condition of metal in the equipment and extending its operation lifecycle is now a no-alternative means of reliable power supply in the country. According to calculations, the volume of funds that are invested in the prolongation of operation is 3–5 times less than that when putting new capacities into service [18].

3. The aim and tasks of the study

The aim of present work is to propose recommendations for extending the operational lifecycle of thermal power equipment based on the calculated research into effect of level and local non-uniformity in temperatures.

To extend reliable operation, the following tasks of research were formulated:

– to devise a technology of micro-torch gas burning in burner devices of the stabilizing type to provide for the regulation of profile and local non-uniformity in temperature field of the combustion products;

– to simulate working processes in burner devices of the stabilizing type during micro-torch gas burning to enable a possibility for temperature regulation of the combustion products;

– calculation assessment of individual resource and development of methodology for the assessment of residual resource of high-temperature elements of heating surfaces of boilers, furnaces, driers, etc., which are exposed to high temperature of gases and local differential in temperatures.

4. Materials and methods of research

Research methods for experimental assessment of the effect of heat flow gradients on the damageability and residual resource of elements include experimental and calculation research into formation of temperature field of gas flows. They also include estimates of the impact of non-uniformity in temperature field on the characteristics of stresses in the elements of equipment.

4. 1. Description of experimental stand

Experimental studies were performed at the experimental stand whose working section is shown in Fig. 1. Air from compressor, through rectifying section 1, throttle grid 2, is supplied to transitional section 3, and, next, to working section 4. The walls of the transitional and working sections are covered with fire-resistant refractory lining 7 and are additionally cooled with water, which is fed through branch pipe 9 to cooling channel 8 and goes through branch pipe 10. To conduct measurements of temperature of gases in the burner space and to take the samples for chemical analysis, there is a system of connections 6.

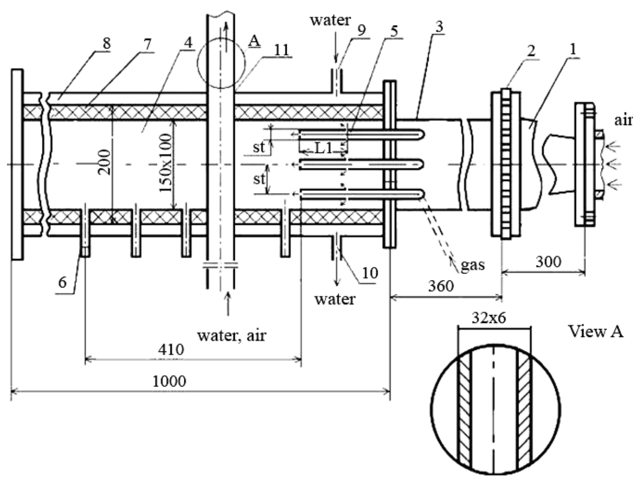


Fig. 1. Experimental stand: 1 – rectifying section; 2 – throttle grid; 3 –transitional section; 4 – working section; 5 – collector-stabilizer; 6 – connection; 7 – fire-resistant refractory lining; 8 – cooling channel; 9 – supply of cooling water; 10 – cooling water discharge; 11 – model branch pipe

The stand is equipped with a system of flat collectors-stabilizers 5, through which fuel (gas) is fed for combustion. Fuel for combustion can be supplied through a system of gas openings in the output front wall of stabilizer into the section of recirculation by stabilizer (gas distribution scheme I). Under such scheme of gas supply, the combustion mode is realized that approaches the diffusion one – relatively long torch, increased burning stability. By the second technique, fuel is supplied by jets for preliminary mixing with air through the system of openings in the side walls of the stabilizer (gas distribution scheme II). In this case, combustion process is similar in its mechanism to the end one with a reduced length of the torch and more intense burning. Thus, a system of torches is formed after the stabilizer, which are divided by the air flow.

When there is a change in the width of stabilizers B_{st}, their number n_{st}, step of placing t_{st}, gas supply scheme and excess air coefficient α, it is possible to establish the required level of gas temperature of the gases t_g, as well as the temperature profile of combustion products along the cross section of the stand. The stand provides for the possibility to install model branch pipes 11 of different size at a different distance from the burner device.

Depending on the set problem, it is possible to feed water or air through the model branch pipe, the consumption and rate of which are regulated.

Design of the stand makes it possible to measure and control the temperature of gases, air speed field, concentration of gas at isothermal blowing and the composition of reaction products at burning.

4. 2. Estimated assessment of the effect of heat flow gradients on the damageability and residual resource of the elements

The second stage of research into thermal condition of the pipeline in a boiler plant is to build spatial 3D analog of a boiler plant (Fig. 2). We built a complex model that includes a burner device and cylindrical pipe of diameter 36×6 mm and length 150 mm. A stream of gases that were formed after the burning device flows around the cylindrical pipe. Burner device is made of three stabilizers of width B_{st}=15 mm, put in the channel of width 150 mm with step t_{st}=50 mm. Shading coefficient is k_f=0.30. Distance from the burning device to the cylindrical pipe was equal to 110 mm and 50 mm. We accepted that the gas temperature at the cross section of stabilizers was t_g=(1000–1300) K. Air temperature was equal to T_a=300 K. Rate of gases was accepted equal to w_g=10 m/s. As the medium that accepts heat in the pipeline, we used feed water at temperature t_w=20 °C and rate w_w=0.5 m/s. As the boundary conditions in thermal calculations, we set BC of types I–IV. Coefficients of heat transfer for gas were at the level of (80–100) W/(m^{2}K); for feed water, heat transfer coefficients were equal to (300–500) W/(m^{2}K).

At the section of length X=110 mm between the burner device and the pipeline, there occurs a mass exchange between the hot trace gases after the stabilizer and cold air in the gap between stabilizers. In the back part of the stabilizer, as a result of intensive mass exchange, temperature in the area of recirculation somewhat levels and its magnitude is at the level of 400 °C. Full leveling, however, does not happen and there is only some smoothing of the temperature profile. Cold water of temperature t_w=20 °C was fed to the internal cavity of the pipeline, and the directions of water flow and hot gases flow were perpendicular. A large set difference in temperatures between hot gases and cold water allowed us to verify the estimated model of hydrodynamics, thermal and the stress-strained state of the pipeline.

The problem of non-stationary thermal conductivity of cylindrical pipe is solved using equation of the form [19]:

$$\mathrm{div}\left[\lambda(T)\,\mathrm{grad}T\right]=c(T)\gamma(T)\frac{\partial T}{\partial \tau}, \quad (1)$$

where λ, c, γ are the functions of temperature and coordinates at initial conditions T_0=T(x, y, z, 0)=f_0(x, y, z) and boundary conditions of type I, II, III, or IV.

Heat emission coefficients α for different zones of cylindrical pipe were determined according to criterion equations at convective heat exchange (BC are set at the surface of cylindrical pipe) and in the course of calculation studies of gas dynamics of the flow of working bodies (hot fuel mixture and water) by the software package Solid Works Simulation (France) [20]. As well as during calculation studies of gas dynamics of working bodies (hot fuel mixture and water) by the software package ANSIS Fluent (USA) [21].

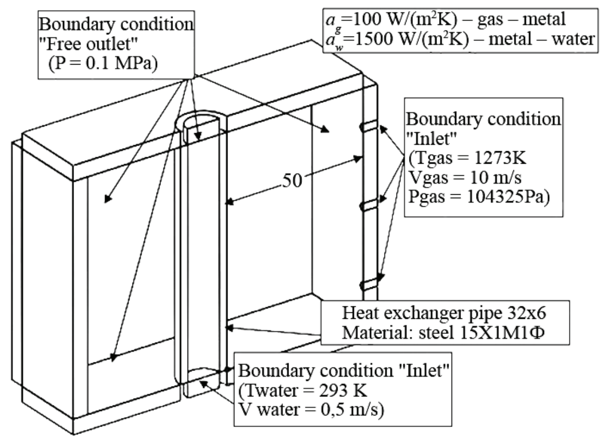


Fig. 2. Geometric model and boundary conditions of cylindrical branch pipe

The stress-strained state of power equipment was calculated during joint solving the equations of equilibrium, which in tensor form are recorded as:

$$\left\{\sigma_{il}\right\}j+\rho X_i=0;\ i,j=1,2,3,\ p_i=f\left(x,y,z,0\right), \quad (2)$$

where σ_i are the normal and shear stresses in the elements of cylindrical pipe; X_i is the mass force which acts in the elements of cylindrical pipe; p_i are the external distributed stresses; ρ_i is the density of material.

We also added equations that describe a simultaneous action of deformations and the law of elasticity, which in matrix form are recorded as:

$$\left\{\varepsilon_{ij}\right\}=\left[a\right]\left\{\sigma_{ij}\right\}+\left\{\beta\times\Delta T\right\}, \quad (3)$$

where $\{\varepsilon_{ij}\}$ is the vector of deformations; [a] is the matrix of elastic coefficients; $\{\sigma_{ij}\}$ is the vector of stresses; {β×ΔT} is the vector of temperature deformations; β is the coefficient of linear expansion; ΔT is the change in temperature of cylindrical pipe during operation.

Based on the non-stationary stressed-strained state, an evaluation of low cycle fatigue is conducted and static damageability of cylindrical branch pipe according to articles [22–24]. The temperatures of metal of cylindrical branch pipe received are needed for subsequent calculating the number of cycles prior to destruction. Control estimated temperature of metal in particular points was chosen by the maximum stress in a fixed period. The use, according to [22], of nominal temperature of metal causes unjustified reduction in the resource indicators of elements of steam turbine and makes sense only at the stage of designing new equipment.

Based on the analysis of existing stresses and temperature fields, we select the most stressed sections of the branch pipe, for which the estimation of low cycle fatigue and static damageability is carried out.

The total damage, accumulated in the metal of cylindrical branch pipe, and remaining operating time prior to a crack formation was determined according to [24].

5. Results of research into calculated and experimental assessment of effect of heat flow gradients on the damageability and residual resource of the elements

5. 1. Thermal structure of the flow in burner devices with stabilizers when the combustion products flow into them

Fig. 3 shows temperature fields of combustion products after stabilizers in different cross sections of the channel during gas burning.

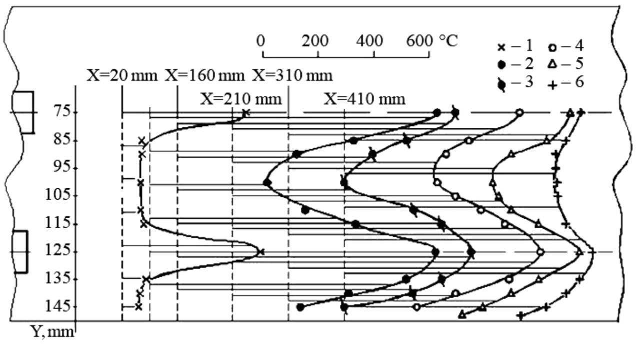


Fig. 3. Temperature fields in burner space when fuel is fed by scheme II (to the streamlined air) at different distances from the stabilizers: 1 – x=20 mm; 2 – 110 mm; 3 – 160 mm; 4 – 210 mm; 5 – 310 mm; 6 – 410 mm

Width of the stabilizer during research was B_{st}=15.0 mm, step of stabilizers location t_{st}=50 mm, shading coefficient of burner B_{st}/t_{st}=0.30.

As can be seen from Fig. 3, in the course of development of the process of fuel burnout, the formation of gas temperature field occurs. Depending on the width of the stabilizer, and the step of location, coefficient of excess air, as well as the distance from the burning device, it is possible to receive the required level of temperature and degree of local non-uniformity.

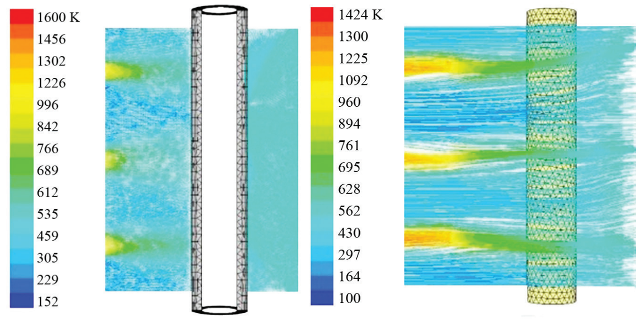
In order to intensify the process of combustion at the same (or even less) hydraulic consumption in the combustion chamber, it is expedient to increase the number of stabilizers of small dimensions. Minimum size of the stabilizer should be chosen so that it is possible to provide for stable burning in the assigned range of parameters of combustible mixture flow.

5. 2. Gas-dynamic and thermal structure of the flow in burner devices with stabilizers during combustion of gas (ANSYS Fluent)

Gas-dynamic characteristics of the estimated model are shown in Fig. 4. In this case, the branch pipe was placed at a distance of x=110 mm from the stabilizer. Vectors of velocity of combustion products and air that flow into the pipeline (Fig. 4, *a*) are received by calculation and indicate the nature of streamlining the model and direction of flowing lines (Fig. 4, *b*). Color of vector corresponds to its temperature. It is clear from the depicted model that zones with temperature 1000 K in the trace after the stabilizer alternated with zones of temperature 300 K on the axis of the slit.

An epure of vector flow by a flux of gases in the cross section of the pipeline (Fig. 5) shows that, in addition to ordinary, there are additional vortex zones beyond the pipeline.

This is related to the fact that in the calculations we considered a variant when the wall of the boiler plant was at a distance of 50 mm from the pipeline, which affected secondary vortex formation.



a *b*

Fig. 4. Vectors of velocity, lines of flow and temperature of the combustion products and air that flow over the branch pipe (ANSYS Fluent, USA): *a* –vectors of velocity and temperature of combustion products and air; *b* – line of flow and temperature

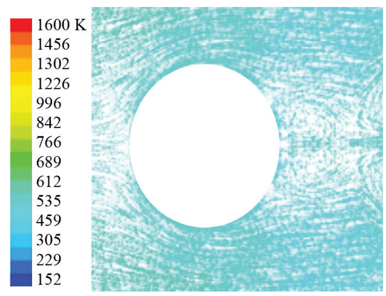
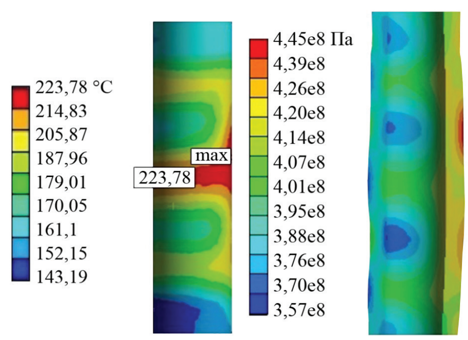


Fig. 5. Epure of vector flow around the branch pipe by a flow of gases (ANSYS Fluent)

Distribution of temperature at the surface of the pipeline (Fig. 6, *a*) indicates a variable thermal condition. Temperature of the pipe's metal is at the level of (223–143) °C. The maximum temperature of the pipeline's metal is registered on the back surface of cylindrical pipe along the passage of hot gas and reaches 224 °C. A considerable level of temperatures is registered at the front surface along the passage of hot gas opposite to the central stabilizer of burning device (from 214 °C to 223 °C). The minimum level of temperatures, in the bottom part of the pipeline, is 143–152 °C.



a *b*

Fig. 6. Epures of temperatures and stresses in the pipeline: *a* – temperatures at the surface of the branch pipe; *b* – distribution of stress intensity by the thickness of the wall (ANSYS Fluent)

The data obtained on the thermal condition of cylindrical pipe are used in the software complex ANSYS as boundary conditions in calculation study of the stressed-strained state using universal package *Static Structural*. The intensity of conditional elastic stresses in cylindrical pipe is in the range of (357–445) MPa (Fig. 6, *b*). Maximum stresses occur at the outer surface of cylindrical pipe. A temperature gradient at the inner and outer surface of cylindrical pipe is about (150–200) °C.

5. 3. Calculation study of the thermal, stressed-strained state of the pipeline in a boiler plant (Solid Works Simulation)

Calculation study of gas dynamics of hot air in a boiler plant, thermal state (TS) and stressed-strained state (SSS) of cylindrical pipe was carried out also with the use of Solid Works Simulation software package. Distance from the burning device to the cylindrical pipe was equal to 50 mm and 110 mm (Fig. 2). A considerable distance to the wall of the boiler plant was behind a cylindrical pipe.

Distribution of temperature by the thickness of the wall of cylindrical pipe (Fig. 7) indicates significant non-uniformity of the thermal state (160–392) °C. This is due to a considerable non-uniformity of hot air temperature in the space of boiler plant, the temperature of hot air is at the level of (110–520) °C. Maximum temperature occurs in orderly direction along the passage of hot gas and reaches 520 °C. A significant level of hot air temperatures is registered before cylindrical pipe along the passage of hot gas opposite to the central stabilizer of burning device (293–427 °C).

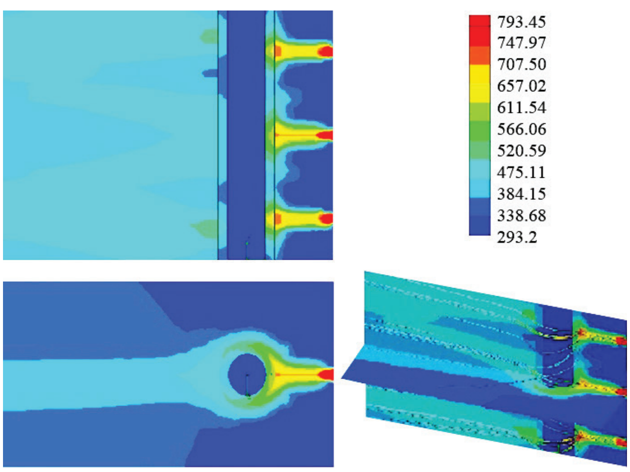


Fig. 7. Distribution of temperatures (K) when cylindrical pipe is flown over by combustion products (Solid Works)

When distance from the burning device to the cylindrical pipe is 110 mm and there is a considerable distance from the cylindrical pipe to the wall of the boiler plant, the distribution of temperature along the length of cylindrical pipe is quite uneven.

5. 3. Calculation study of the stressed-strained state of pipeline in a boiler plant

We found main stresses and intensities of stresses over the period that meets starting requirements [25, 26]. Distribution of temperature by the thickness of the wall (Fig. 8, *a*) indicates a significant temperature gradient across the entire plane of the pipeline. Temperature of pipeline's metal is at the level of (250–300) °C. Maximum temperature of hot gas mixture opposite the central stabilizer of burning device is about 1000 °C. Zones of maximum values of temperatures along the cylindrical pipe are located opposite the stabilizers of burning device, respectively. Temperature non-uniformity along the pipe amounts to 54 % and is correlated with data of experimental studies.

The intensity of conditional elastic stresses in cylindrical pipe is in the range of (370–497) MPa (Fig. 8, *b*), provided the boundary conditions of convective heat exchange are assigned, and in the range of (138–274) MPa (Fig. 9), provided the calculation of gas-dynamic characteristics of hot gas flow that flows around the cylindrical pipe is conducted.

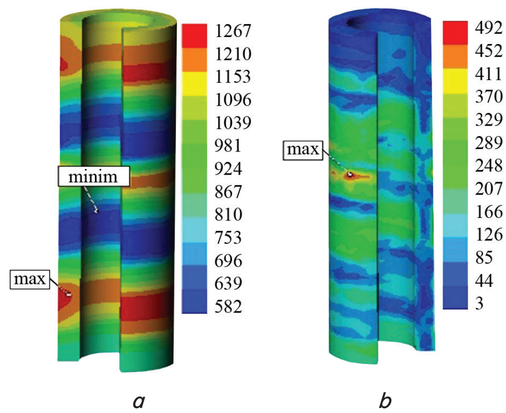


Fig. 8. TS and SSS of cylindrical branch pipe in boiler plant (Solid Works), distance from the burner is 50 mm, BC assigned: *a* – Thermal state (TS), K; *b* – Stressed-strained state (SSS), MPa

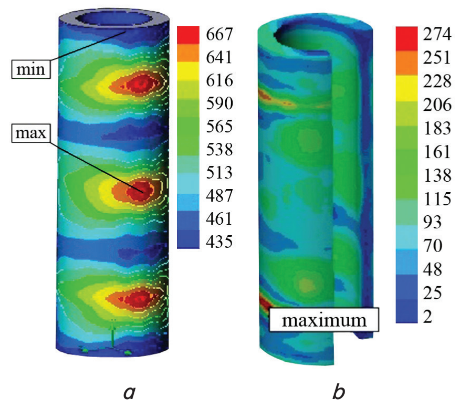


Fig. 9. TS and SSS of cylindrical branch pipe in boiler plant (Solid Works), distance from the burner is 50 mm, calculation of gas-dynamic characteristics: *a* –Thermal state (TS), K; *b* – Stressed-strained state (SSS), MPa

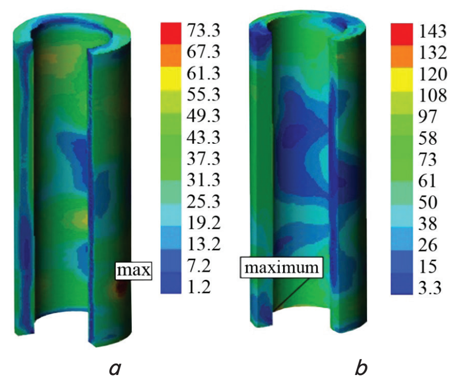


Fig. 10. SSS of cylindrical branch pipe in boiler plant (Solid Works), distance from the burner is 110 mm: *a* – free expansion of branch pipe at the ends; *b* – fastening the branch pipe at the ends

When the distance from the burning device to the cylindrical pipe equaled 110 mm, the distribution of intensity of conditional elastic stresses in cylindrical pipe was equal to (49–73) MPa (Fig. 10, *a*) under condition of free expansion of cylindrical branch pipe at the ends, and to (97–144) MPa (Fig. 10, *b*) when cylindrical branch pipe was fastened at the ends.

5. 4. Calculation study of damageability and residual resource of pipeline in a boiler plant

Calculation assessment of static damage to cylindrical branch pipe in a boiler plant is determined by the maximum tension of metal (144 MPa) and is at the level of 0.57 while time before the onset of boundary condition under the influence of equivalent stresses is determined using a diagram of long-term strength of material [27].

Operational lifecycle of steam pipes in boiler plants, according to [24], is at the level of (100–250) thousand hours. As predicted, over a period following the analysis, an average annual damage that will be accumulated in the examined section of cylindrical branch pipe will amount to 0.019. Residual operational time prior to the occurrence of crack (in years) in a cylindrical branch pipe of boiler plant is 12.9 years and, accordingly, 77400 hours at employing the boiler plant for 6000 hours per year.

6. Discussion of results of research into residual resource of high-temperature elements of energy and industrial equipment

As measurements of temperature of gases in the burner space reveal, as a result of torch temperature fluctuations, even under stationary operation modes, there are changes in the temperature gases observed over time in the same point of the burner space, which may reach significant magnitudes (400–500) °C. This phenomenon leads to significant additional shock stresses in metal.

When burning fuel in the systems of stabilizers, dimensions and configuration of torches for each stabilizer depend on the number of stabilizers and their mutual location. In the case of a uniform placement of stabilizers in one plane (when distance s between the edges of adjacent stabilizers is the same and the distance between the wall and the edge of a nearby stabilizer is equal to s/2), the axes of torches are parallel to the axis of the chamber; behind each of the stabilizers with the same dimensions and geometrical shape, torches have the same size.

Results of calculations using ANSYS Fluent demonstrated that maximum temperature on the wall of the branch pipe is on the back wall of the branch pipe and is equal to 224 °C, minimum temperature in the neighboring section is 160 °C. Such distribution of temperature occurs when the rear surface of the boiler plant is close behind a cylindrical pipe. In case the rear surface of the boiler plant is further apart, cylindrical pipe overheating in the zone behind it disappears.

Maximum value of stress intensity by Mises is 445 MPa in the place of maximum temperature at the rear wall of the branch pipe. Minimum value of stress intensity by Mises at the front surface of the branch pipe in the place of minimum temperature is 357 MPa. Such distribution of stress intensity by Mises can be explained by the nature of fuel combustion as a result of existence of 3 burners. As well as by uneven heating of pipe by thermal flow and perpendicular direction of gas component flow of the gas flow at the outer surface of the branch pipe. Significant influence is exerted by a cooling water component that acts in the inner surface of the branch pipe. Maximum value of stress intensity by Mises at the rear wall of the branch pipe may also occur through the turbulence of gas flow along the pipe and the intensification of heat exchange in this zone.

7. Conclusions

1. We proposed a technology of micro-torch burning of gas in burner devices of stabilizing type to ensure regulation of the profile and local non-uniformity of temperature field of the combustion products. It provided for the opportunity to operate burning device in a wide range of change in the operational parameters. This will lead to the reduction in heat loss with exhaust gases, especially under partial load of the unit, and to improving performance efficiency. At such organization of the combustion process, it is possible to exclude shock thermal effect of the torch on the heating surface. Maximally possible uniformity of distribution of heat flows in the furnace is provided, as well as the length of the torch, which is less than the corresponding dimensions of the furnace.

2. A mathematical model is developed for the combustion process in burner devices with stabilizers based on the software complex ANSYS Fluent. We created a technique for determining the impact of levels of temperatures and their gradients on the assessment of residual resource of high-temperature elements of power and industrial equipment. Based on data on the work of industrial power equipment and results of physical experiments, we chose correct initial and boundary conditions that enabled adequate simulation of the influence of non-uniformity in the combustion products temperature field. Based on the software complex Solid Works, we performed calculation studies that take into account the gas-dynamics of gas flow that flows around the pipeline. The thermal and stress-strained states are defined and an estimation is conducted of operational lifecycle of pipeline in a boiler plant depending on the operating conditions of equipment.

3. Based on the devised method, we carried out assessment of residual operation time of a pipeline, which under the given conditions is 77.4 thousand hours at static damageability from long-term loads of 57 %.

Results of the research conducted might be used by implementing the recommendations proposed in large- and small-scale energy sector, industry and gas transportation system in Ukraine, as well as in other fields of science and technology.

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