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ANALYSIS OF THE STATIC STRENGTH OF THE EMERGENCY-COOLDOWN HEAT EXCHANGER WITH THE USE OF THE DESIGN TIGHTNESS VALUE OF FLANGE-JOINT PINS

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Analysis of the design calculation of the 08.8111.335 SB emergency-cooldown heat exchanger (ECHE) strength revealed a number of deviations from the requirements of current regulations of Ukraine in nuclear energy, which, in particular, include the lack of information on the calculation of the static strength of heat-exchanger flange elements and the excess of allowable stresses in their pins. This article describes a mathematical model for calculating the ECHE thermal stress state, which is used to simulate the ECHE operation under conditions of normal use. A number of computer calculations of ECHE deformation processes were performed using the described equations of the three-dimensional theory of elasticity. Such calculations were performed, using the finite element (FE) method, to analyze the strength of the ECHE and, in particular, elements of its flange joints. Results of ECHE static strength calculations are given. The calculations were performed using the general FE model of the ECHE, the model including all its basic elements. In addition, individual FE models of ECHE flange joint elements DN2130 and DN2080 were developed, on whose basis their static strength calculations were performed. As a result of calculations of the strength of the main ECHE elements, it is concluded that the operating stresses for the considered groups of categories of design stresses in the design zones of the ECHE design do not exceed the allowable values, and, accordingly, the static strength conditions are met. Given the symmetry of ECHE flange joints, FE models of the half-period of one bolted joint were used to calculate their static joint strength. The main boundary conditions for all calculations were: the tightening force of pins, as well as the pressure and temperature of the operating environment. The calculation of the static strength of the flange joint elements DN2130 and DN2080, using the design value of the pre-tightening force of the pins, showed that the conditions of static strength are not met for the considered groups of categories of design stresses.

***Keywords**: emergency cooldown heat exchanger, extension of service life, design substantiation of safe operation, assessment of technical condition, thermal stress state of the ECHE, FE method.*

Introduction

One of the priority areas of operation of existing nuclear power plants (NPPs) in Ukraine is to extend their service life. Within this area, a wide range of work is carried out, one of which is technical condition assessment whose purpose is to confirm the safe operation of reactor plant elements in the beyond-design period. As part of technical condition assessment, strength and reliability analysis works are performed in accordance with [1] and [2]. It should be noted that these works must be performed in compliance with the requirements of modern nuclear energy standards of Ukraine.

As the experience of the analysis of design strength calculations [3] shows, when solving the problem of substantiating the safe operation of the ECHE, special attention should be paid to its flange joint elements. Given the significant development of electronic computers, it is possible to calculate the strength of complex, in terms of geometry, units of equipment, using the FE method.

This article describes the mathematical model of the FE method and approaches to calculating the strength of the main ECHE elements.

Statement and Solution of the Problem of the ECHE Static Strength

The task is to determine the thermoelastic state of the ECHE under conditions of normal use. At the first stage of consideration of the problem we assume that in the course of the ECHE operation, deformations are elastic and such that allow one to use geometrically linear relations of the general theory of elasticity. In the case of detection of areas with the stress exceeding the yield strength, further calculation must be performed using equations of thermoelasticity.

We formulate a mathematical model for calculating the thermoelastic state of the ECHE, providing it operates under normal conditions. It should be noted that the ECHE design is made up of various noncanonical-shape elements with uneven surfaces. Particularly complex elements of geometry are both in the area where individual structural elements are joined and in areas of abrupt change in the geometric configuration of the ECHE. Therefore, the use of generally accepted assumptions of the theory of shells and the use of analytical calculations of complex-geometry bodies can lead to significant errors. Based on this, to calculate the ECHE strength we used a three-dimensional problem statement, which allows us, with a sufficient degree of adequacy, to describe the stress state of structures.

Consider the ECHE as a three-dimensional elastic body occupying the region Ω of the Euclidean space *S*. According to the theory of the FE method, we assume that the ECHE consists of a number of individual three-dimensional FEs. Next, consider one such FE in the coordinate system *x*, *y* and *z*.

The stress-strain state of a body is characterized by displacement vectors δ, strain tensors ε, and stress tensors σ. The displacement vectors take into account the components $u = u(x, y, z)$, $v = v(x, y, z)$, $w = w(x, y, z)$, which indicate the displacement of the *x*, *y* and *z* axes, respectively. The strain tensors are divided into the linear tensors ε_x, ε_y, ε_z and angular ones γ_{xy}, γ_{yz}, γ_{zx}. The stresses are divided into the normal stresses σ_x, σ_y, σ_z and tangent ones τ_{xy}, τ_{yz}, τ_{zx}. The complete system of the problem of elastic body statics consists of the following relations [4], [5]:

– Cauchy ratio

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{du_i}{dx_j} + \frac{du_j}{dx_i}\right), \tag{1}$$

– Hooke's law

$$\sigma_{ij} = \left(\frac{Ev}{(1+v)(1-2v)}\delta_{ij} + 2\mu\right) \cdot \varepsilon_{ij}, \tag{2}$$

– equilibrium equation

$$\frac{d\sigma_{ij}}{dx_j} + p_i F_i = 0, \tag{3}$$

– stress boundary conditions

$$N_i \sigma_{ij} = p_i, \tag{4}$$

– displacement boundary conditions

$$u_i = u_i^*, \text{ при } r \in S_u, \tag{5}$$

where ε_{ij}, σ_{ij} are components of the strain and stress tensors; F_i, N_i are vector components of the mass force *F* and a unit normal vector *N* to the surface $S = S_u \cup S_\sigma$; *r* is the radius vector of the point (*x*, *y*, *z*); p_i is the vector of forces distributed over the body volume; *E* is Young's modulus; ν is Poisson’s module; μ is the shear modulus; δ_{ij} is the Kronecker symbol; *i*, *j*=1, 2, 3.

Relations (1)–(3) and boundary conditions (4), (5) constitute a complete system of equations of the static problem of the theory of elasticity.

However, it is not always possible to obtain an analytical solution for complex-geometry bodies. Therefore, numerical methods, in particular the FE method, are widely used to solve such problems. The most natural is the variational formulation of the problem of the theory of elasticity.

Variational Problem Statement

The basis for the variational formulation of the problem is the mathematical formulation of the static problem of the theory of elasticity in displacements in the form of the Lagrange variational principle.

The Cauchy relationship (1) and Hooke's law (2) can be written in matrix form by entering the matrix differential operators [B] and [D]

$$\{\varepsilon\} = [B] \cdot u , \tag{6}$$

$$\{\sigma\} = [D] \cdot (\{\varepsilon\} - \{\varepsilon_T\}) , \tag{7}$$

where $\{\varepsilon_T\} = \{\alpha \cdot \theta, \alpha \cdot \theta, \alpha \cdot \theta, 0,0,0\}$ is the vector of temperature deformations (α is the thermal expansion coefficient, θ is the average element temperature).

The amount of the potential energy stored by the element during deformation can be found using the following formula:

$$\Pi_e(u) = \frac{1}{2} \int_v \{\sigma\}^{\mathrm{T}} \{p\} dv - \int_v \{\delta\}^{\mathrm{T}} \{p\} dv - \int_v \{\delta\}^{\mathrm{T}} \{q\} ds . \tag{8}$$

Given the division of the body Ω into n-number of FEs, the total potential energy of the elastic deformation of the body is determined by adding the elementary contributions of each of the FEs

$$\Pi(u) = \sum_{e=1}^{n_e} \Pi_e(u) .$$

Thus, in this statement, the problem of determining the stress-strain state of the body Ω subjected to temperature and force load is reduced to finding the minimum of function (8) on the set V. In other words, for relations (1)–(5), determined are such equation solutions at which the following variational problem is solved:

$$\Pi(u) \xrightarrow[u \in v]{} \min .$$

When solving this problem, strains (6) are first determined, and then, stresses (7).

This mathematical formulation of the problem is used to determine the thermal stress state of ECHEs of power unit No. 4 of Zaporizhzhia NPP under static power and temperature load. The three-dimensional approach allows us to adequately take into account the complex geometric shape and investigate the thermal stress state of the ECHE. It also makes it possible to more accurately assess the level of stress in places of local stress concentration.

Calculation of the ECHE Strength by the FE Method

Solving the problem of calculating the ECHE static strength, using the above method included:

– construction of a FE model of the geometric configuration and fields of ECHE displacements;

– obtainment and solution, on this basis, of equilibrium equations in the form of a system of linear algebraic equations with respect to unknown nodal displacements;

– determination of the stress state of the ECHE.

Using the equations of the three-dimensional theory of elasticity, a number of calculations of the thermoelastic state of the ECHE under conditions of its normal operation were performed. During the formation of the ECHE FE model, the factory, design and operational documentation (drawings, design strength calculation, passport, etc.) were used. The values of allowable stress values were determined using the values of the tensile strength and yield strength given in [6].

A general view of the ECHE is shown in Fig. 1.

The main operating parameters of the ECHE are given in table 1. The working-environment pressure and temperature values used in the calculations of the ECHE strength were taken in accordance with [8].

All the ECHE elements are made of corrosion-resistant heat-resistant steel 08X18H10T and flange joint pins, of steel XH35BT. According to [6], during the calculation, the physical and mechanical properties of materials corresponding to temperatures of +70 °C and +150 °C were taken into account.

According to the norms [6], for the corresponding groups of categories of the design stresses that occur in the ECHE elements, their permissible values were determined, which are given in table 2.

The general view of the ECHE FE calculation model, which includes all the main elements, is shown in Fig. 2. This model includes 92,722 nodes and 287,064 FEs.

The kinematic boundary conditions of the ECHE were set in the form of a prohibition of all structural displacements and rotations in the fixed support, as well as the permission of displacements in the movable support along the ECHE longitudinal axis (see Fig. 1).

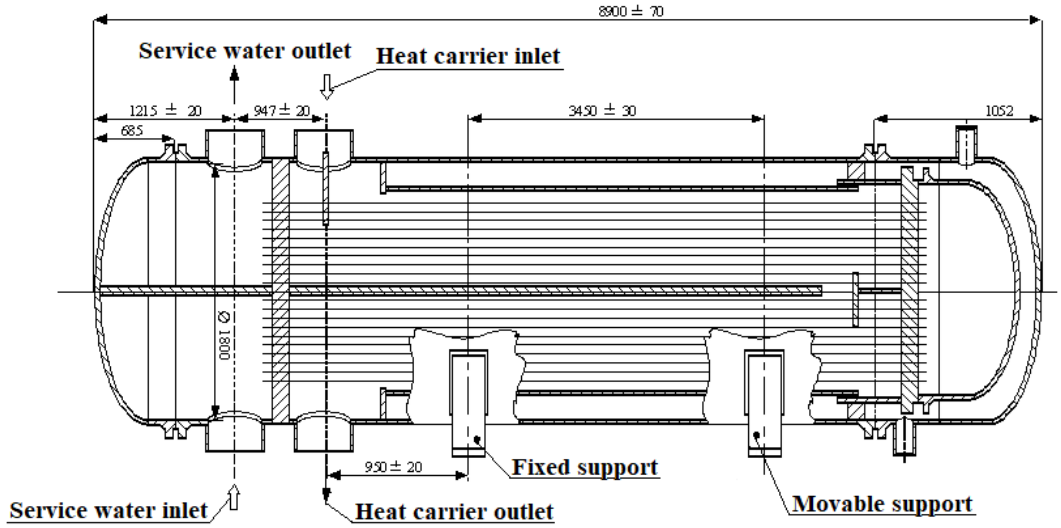

Fig. 1. Overall dimensions of the ECHE

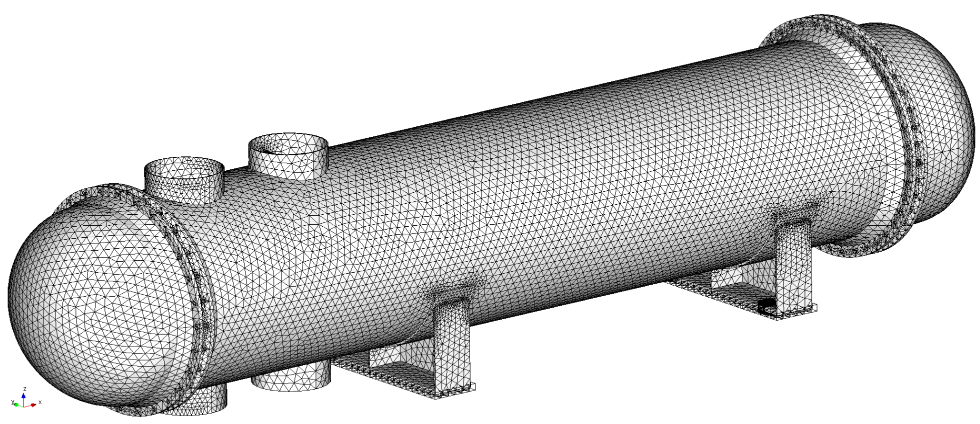

Fig. 2. Calculation model of the ECHE

Table 1. Basic calculation parameters

Name of ECHE environment	Pressure values, MPa	Temperature values, °C	Operating environment
Body	2.1	+150	H_3BO_3 solution 16g/kg
Pipe part	0.5	+70	Service water of group "A"

Table 2. Values of allowable stresses

Type of structure	Allowable stress values for corresponding groups at design tempeature, MPa					
	$(\sigma)_1$ or $(\sigma)_{mw}$		$(\sigma)_2$ or $(\sigma)_{3w}$		$(\sigma)_{RV}$ or $(\sigma)_{4w}$	
	150 °C	70 °C	150 °C	70 °C	150 °C	70 °C
Pins	181.50	193.10	235.95	251.03	308.55	328.27
Body elements	124.00	126.80	161.20	164.84	372.00	380.40
Weld seams	190.92	201.00	248.19	261.30	496.40	522.60

Force boundary conditions were taken into account in the form of
– ECHE's own weight;
– mass of liquid;
– pressure and temperature of the operating environment;
– load from the attached ECHE lines (forces and moments);
– tightening forces of flange joint pins.

To correctly set the loads from the attached ECHE lines, the strength calculations for the service-water system segments and the emergency cooling system of the active zone of power unit No. 4 of Zaporizhzhia NPP were performed. During the strength calculations, the geometry of the lines, weight-and-dimentional characteristics, attachment points and technical parameters of the internal environment were taken into account. The above lines were modeled using two-node pipe-type rod elements. The developed models of the lines take into account the segments from ECHE branch pipes and to the nearest fixed supports. This approach allows one to assert the correctness of taking into account the loads on ECHE branch pipes from the attached lines.

Loads on ECHE branch pipes from the attached lines, which were taken into account during static strength calculation, are given in table 3.

Table 3. Forces and moments from the attached lines

Forces, *N*			Moments, N·mm		
R_x	R_y	R_z,	M_x	M_y	M_z
Service water inlet					
21,985	2,353	11,827	-1,167,825	7,868,516	127,567
Service water outlet					
1,124	-2,385	20,220	-8,763,668	-7,113,462	-1,049,489
Distillate product inlet					
-4,259	769	18,416	16,380	4,659	-6,368
Distillate product outlet					
-187	-2,211	18,007	1,318	2,176	2,094

As a result of the calculations performed using the FE method, the values of stresses in the main ECHE elements are obtained for normal operating conditions. Graphical view of the distribution of equivalent stresses by maximum shearing stress theory (SMAXTAU) is shown in Fig. 3, 4. The results of stresses and their comparison with the allowable values are given in table 4.

The analysis of the obtained results shows that the largest values of stresses occur at the place where the dividing plate is welded to the inner surface of the branch pipe inlet for the heat carrier (point 4). These stresses are local in nature and are caused to a greater extent by the ECHE structure geometry and the loads from the heat carrier pressure.

The operating stresses in groups of categories of the design stresses $(\sigma)_1$, $(\sigma)_2$ and $(\sigma)_{RV}$ in the design zones of the ECHE structure do not exceed the allowable stress values for these groups, and, accordingly, the static strength conditions are met.

Table 4. Stress in ECHE elements

ECHE element	Point	$(\sigma)_1$, MPa	Allowable stress, MPa	$(\sigma)_2$, MPa	Allowable stress, MPa	$(\sigma)_{RV}$, MPa	Allowable stress, MPa
Main elements							
ECHE body	1	82.76	124.00	125.35	161.20	213.10	372.00
Inter-tubular environment chamber	2	39.00		61.01		64.89	
Branch pipes	3	47.42		79.76		94.20	
	5	84.58		101.30		124.20	
Weld seams							
Between dividing plate and branch pipe	4	145.68	190.92	192.34	248.19	244.50	496.40
Between inter-tubular environment chamber and internal casing	6	52.12		52.12		119.90	
Between flange and body	7	49.50		56.08		54.54	
Between inter-tubular environment chamber and body	8	26.86		81.03		81.12	

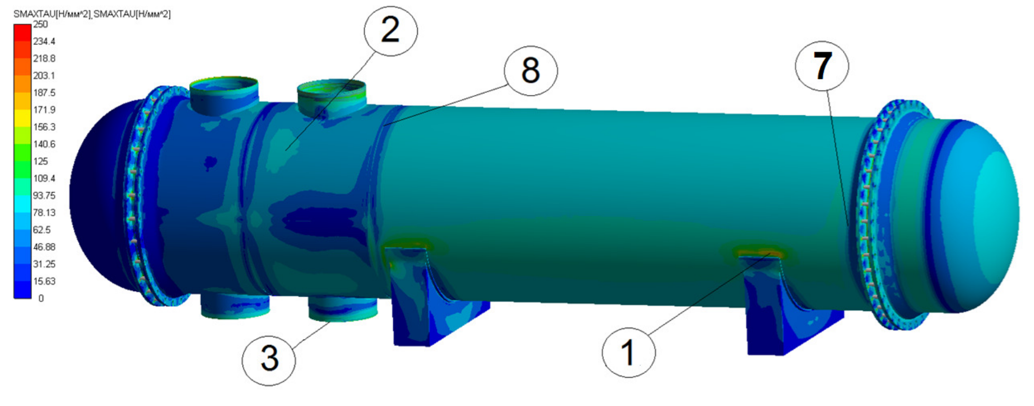

Fig. 3. Distribution of equivalent stresses in ECHE elements

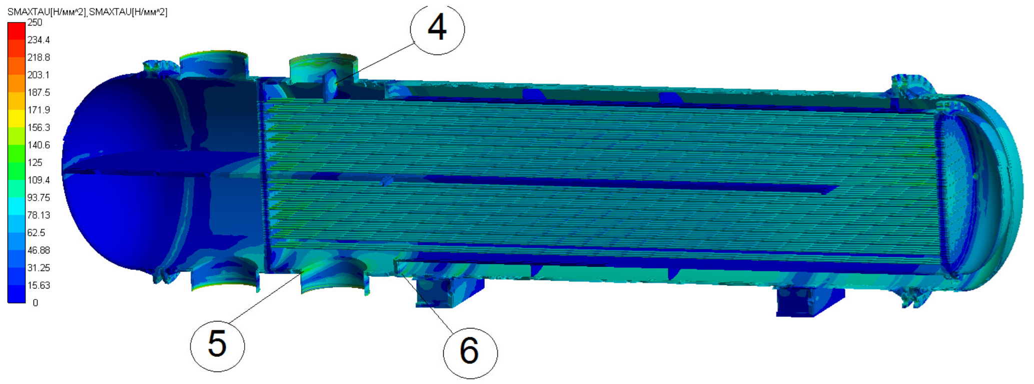

Fig. 4. Distribution of equivalent stresses in ECHE elements (sectional view)

Calculation of the static strength of ECHE Flange Joint Elements

ECHE flange joints have a symmetrical design. In order to reduce the dimensionality of the task of calculating the strength of flange joints, modeling of cutaways with the appropriate conditions of symmetry was performed. To calculate the static strength of flange joint elements, individual FE models of the half-period of one bolted joint were developed.

The half-period consists of a half-period of flanges proper, corresponding parts of transition cones, shells, elliptical bottoms and half of a pin with two halves of nuts.

According to [7], the pins of the flange joints Dn2130, Dn2080 and Dn1780 should be tightened with a torque of 246, 84, 85 kg·m, respectively, which correspond to pre-tightening forces of 22,527 kgf, 8,836 kgf, and 8,900 kgf.

The calculation of the static strength of flange joint elements showed that for the flange joints Dn2130 and Dn2080 the conditions of static strength are not met. Therefore, in the future, the results of calculations of the strength of the elements of the flange joints DN2130 and DN2080 will be presented.

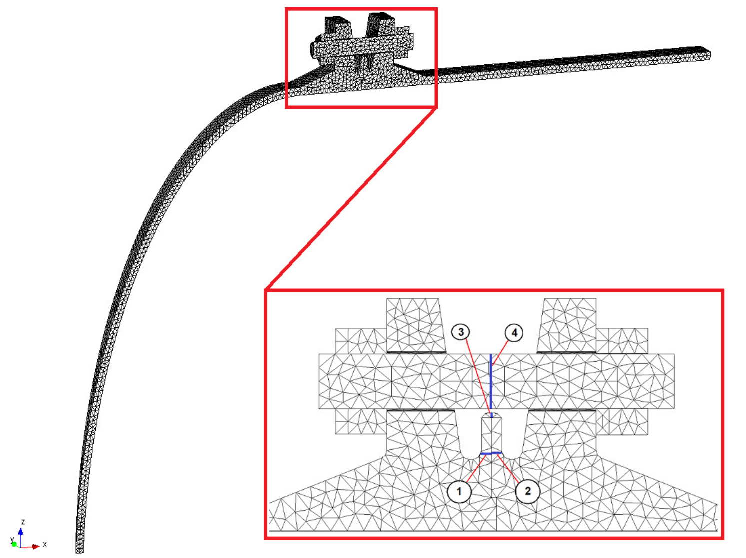

Fig. 6. General view of the half-period model of the flange joints Dn2130 and Dn2080

The general view of the half-period model of the flange joints DN2130 and DN2080, as well as the points of their most loaded elements: weld wiskers for weld build-up (1, 2), weld build-up (3) and a pin (4) are shown in Fig. 6.

Figs. 7 and 8 show the results of calculation of equivalent stresses by maximum shearing stress theory (SMAXTAU) for the half-period model of flange joints Dn2130 and Dn2080 under normal operating conditions, the results having been obtained taking into account the design values of pin tightening.

The results of the stress calculation for the flange joints DN2130 and DN2080 as well as of their comparison with the available values for the respective groups of categories of design stresses are given in tables 5 and 6.

Excessive allowable values for some stress groups were found in such elements of flange joints as pins (point 4 in Fig. 6) and weld whiskers (points 1 and 2 in Fig. 6). High stresses in flange joint elements are explained by the fact that due to the effect of "protrusion" under the action of pressure of the bottom and shell attached to the flanges, as well as depending on the tightening force of the pins, the equilibrium conditions of applied force vectors changes, which in turn leads to additional deformations of flange joint elements.

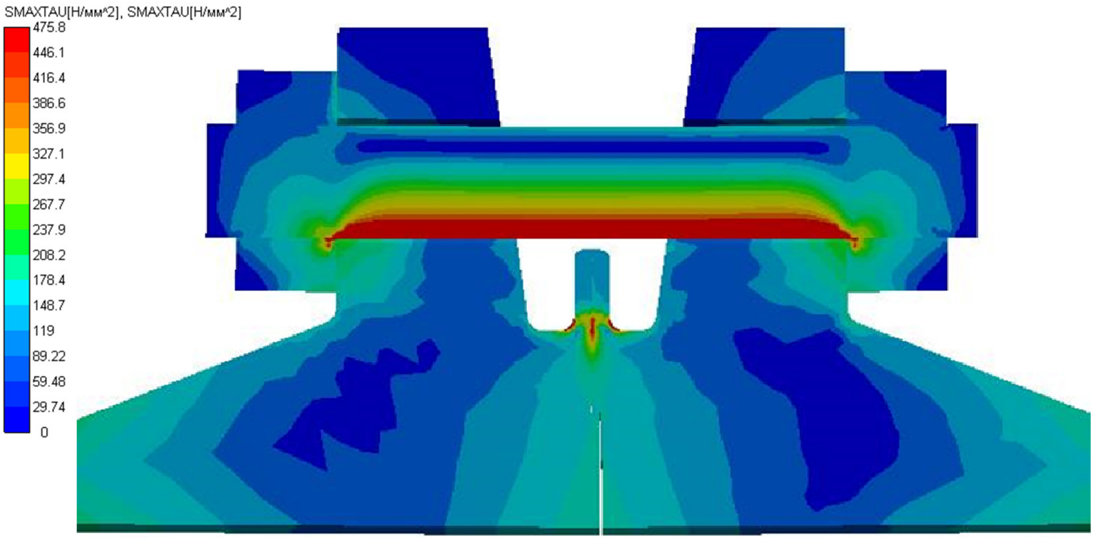

Fig. 7. Results of the equivalent stress calculation for the flange joint Dn2130

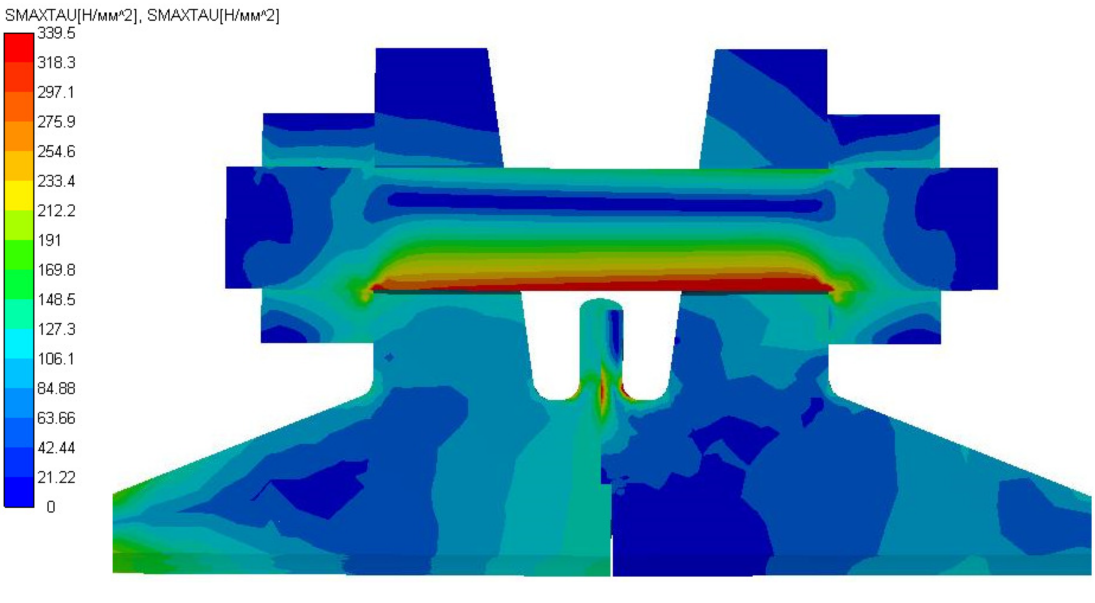

Fig 8. Results of the equivalent stress calculation for the flange joint DN2080

Table 5. Stresses in elements of the half-period of the flange joint DN2130

Flanged joint element	$(\sigma)_1$ or $(\sigma)_{mw}$, MPa	Allowable stress, MPa	$(\sigma)_2$ or $(\sigma)_{3w}$, MPa	Allowable stress, MPa	$(\sigma)_{RV}$ or $(\sigma)_{4w}$, MPa	Allowable stress, MPa
Pin	172.02	181.50	195.32	235.95	372.41	308.55
Weld build-up	96.40	190.92	96.20	248.19	88.29	496.40
Weld whisker (point 1)	216.81	124.00	244.41	161.20	470.47	372.00
Weld whisker (point 2)	218.89		236.82		455.85	

Table 6. Stresses in elements of the half-period of the flange joint DN2080

Flange joint element	$(\sigma)_1$ or $(\sigma)_{mw}$, MPa	Allowable stress, MPa	$(\sigma)_2$ or $(\sigma)_{3w}$, MPa	Allowable stress, MPa	$(\sigma)_{RV}$ or $(\sigma)_{4w}$, MPa	Allowable stress, MPa
Pin	98.27	193.10	280.24	251.03	339.16	328.27
Weld build-up	43.60	201.00	44.08	261.30	127.86	522.60
Weld whisker (point 1)	68.82	126.80	204.98	164.84	309.96	380.40
Weld whisker (point 2)	67.71		211.32		205.23	

It should be noted that the values of the stresses of pins of the flanged joints Dn2130 and Dn2080 in the group of the stresses $(\sigma)_{3w}$, obtained by calculation, coincide with the values specified in document [7], which indicates the correctness of the calculation models and calculations in general. The groups of the stresses $(\sigma)_{mw}$ and $(\sigma)_{4w}$ were not considered in document [7].

Conclusions

The static strength of the ECHE under normal operating conditions is calculated. Strength calculations are performed with the setting of all boundary conditions that occur under these ECHE operating conditions. The obtained results confirm the fulfillment of the strength conditions [6] of the main elements of the ECHE. However, a detailed analysis of the strength of elements of the flange joints Dn2130 and Dn2080 shows that the allowable values of stresses in their pins and weld whiskers are exceeded. Given that the ECHE belongs to the equipment of systems important for the safety of the reactor unit, and there is a failure to meet the strength conditions of elements of the flange connections DN2130 and DN2080, it is advisable to determine the conditions under which the safe operation of the ECHE is possible.

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Аналіз статичної міцності теплообмінника аварійного розхолоджування з використанням проектного значення затягу шпильок фланцевих з’єднань

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Аналіз проектного розрахунку міцності теплообмінника аварійного розхолоджування 08.8111.335 СБ (ТОАР) виявив низку відхилень від вимог чинних нормативних документів України в атомній енергетиці, зокрема, до них належить відсутність відомостей щодо розрахунку статичної міцності елементів фланцевих з’єднань теплообмінника та перевищення значень допустимих напружень у шпильках. У цій статті описано математичну модель розрахунку термонапруженого стану ТОАР, за допомогою якої виконано моделювання його роботи в умовах нормальної експлуатації. З використанням описаних рівнянь тривимірної теорії пружності виконано ряд комп’ютерних розрахунків процесів деформування розглянутого теплообмінника. Такі розрахунки проведені з метою аналізу міцності ТОАР та його елементів фланцевих з’єднань, зокрема, та виконані з використанням методу скінченних елементів. Наведено результати розрахунків статичної міцності ТОАР, виконаних з використанням загальної скінченноелементної моделі теплообмінника, що включає усі основні його елементи. Додатково розроблено окремі скінченноелементні моделі елементів фланцевих з’єднань Дн2130 та Дн2080 ТОАР, на основі яких виконано розрахунки їх статичної міцності. В результаті проведених розрахунків міцності основних елементів ТОАР зроблено висновок, що діючі напруження за розглянутими групами категорій наведених напружень в розрахункових зонах конструкції теплообмінника не перевищують допустимих значень, відповідно, умови статичної міцності виконуються. Враховуючи симетрію фланцевих з’єднань теплообмінника, для їх розрахунку на статичну міцність використовувались скінченноелементні моделі напівперіоду одного болтового зчеплення. Основними граничними умовами для всіх розрахунків були: сила затягнення шпильок, тиск та температура робочого середовища. Розрахунок статичної міцності елементів фланцевих з’єднань Дн2130 та Дн2080, з використанням проектного значення сили попереднього затягнення шпильок, показав, що умови статичної міцності не виконуються для розглянутих груп категорій наведених напружень.

***Ключові слова**: теплообмінник аварійного розхолоджування, продовження терміну експлуатації, розрахункове обґрунтування безпечної експлуатації, оцінка технічного стану, термонапружений стан теплообмінника, метод скінченних елементів.*

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