ISBN: 978-3-95450-240-0 ISSN: 2673-5539 doi:10.18429/JACoW-RuPAC2021-WEPSC06

ASESS INPUT DATA UNCERTAINTIES IN THERMAL-MECHANICAL CALCULATIONS OF THE OUTLET WINDOW MEMBRANE OF THE LUE-200 ACCELERATOR

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Abstract

The maximum values of the temperature fields and stress-strain state are calculated for various configurations of the outlet window membrane of the LUE-200 accelerator with assessing uncertainties in input data. The thermomechanical parameters are estimated by simulating the electron beam pulsed action mode on the membrane in the computational models based on the mathematical description of the most significant physical processes. The obtained numerical modelling results demonstrated the importance of assessing uncertainties in input data for substantiating the safe operation limits of IREN facility.

INTRODUCTION

The paper clarifies the previously obtained estimates by reducing the error influence in the calculation results, due to the assumptions and approximations adopted in [1], as well as the uncertainty and formalism when specifying the initial data. A change in the approaches in combination with the development of the initial data processing methods are capable of giving a more detailed description of physical processes and contribute to the further improvement of the membrane assembly design [2, 3].

MODEL DESCRIPTION

A thermomechanical problem is focused on evaluating the temperatures field and stress-strain state (SSS) arising on the membrane during the installation operation. The solution of a problem was performed by the method of running finite difference equations reduced to the standard three-diagonal form. The mathematical formulation of the heat conduction problem [4, 5] and the elasticity theory [4, 5, 6] have the following form:

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = LT + E(E_e, r, h) \cdot I(\tau), \quad (1)$$

$$\rho \frac{\partial^2 U}{\partial t^2} = LU + P + \alpha_{ex} \cdot (3k + 2\mu) \cdot grad\,\theta, \quad (2)$$

where: T is the temperature; U is a deformation; ρ is the density; L is a differentiating operator; E is energy deposition; I is beam current; τ is pulse duration; k and μ are the Lamé constants; α_{ex} is the coefficient of linear thermal expansion of the medium; $\theta = T\text{-}T_0$ – temperature deviation; P is the applied force.

A. A. Samarskii's discretization scheme [4] is used to solve the heat conduction problem. It is stable and has the total approximation property.

Obtained from the measurements of the Rogowski belt beam current the experimental data ($I(\tau)$ diagrams), the normalized distribution of the energy release in the membrane, taking into account the distribution of the current density over the beam cross section [1], the thermos-physical characteristics of structural materials, and the environmental parameters are used as the initial data for calculating the SSS and temperature fields.

Estimation of the Properties

Based on the calculation model work results an assessment of the impulse characteristics of the thermos-mechanical operating mode of the outlet window membrane became available. Let's consider a mode of operation with a limited power level and carry out the necessary calculations. The current IREN facility parameters by neutron yield determine the average electron beam power P_{av} ~ 1.1 kW at a pulse duration of τ = 250 ns, the beam current in the pulse I = 0.63 A, the electron energy in the beam at the level of E = 70 MeV, and the pulse repetition rate f = 100 Hz. Single pulse simulation (Fig. 1) was carried out in order to verify the correct operation and applicability of the developed computational model for assessing the thermal-mechanical characteristics of the membrane in a pulsed mode. In that case, the calculation model of the membrane experiences a single pulse action of an electron beam, described by the course of the averaged interpolated curve. The membrane, being previously in a cold state at room temperature, starts to warm up in proportion to the transmitted by the beam power. The cooling rate of the membrane heated after the pulse depends on the membrane material thermal inertia, which is a function of convective heat transfer and thermal conductivity.

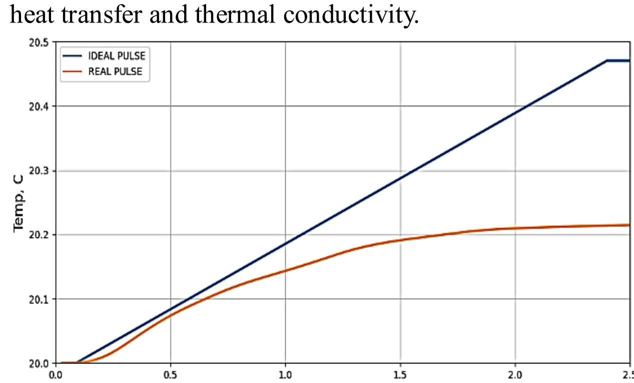

Figure 1: Single pulse.

The subsequent simulation of the installation pulsed operation mode is similar to a single pulse simulation, which is sequentially included in the time series of events f (frequency) times. The steady-state thermo-mechanical characteristics of the membrane for the selected operating mode are shown in Fig. 2 and Fig. 3.

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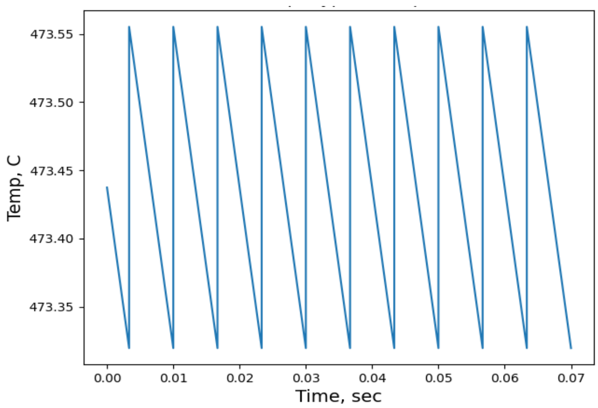

Figure 2: Pulse heating.

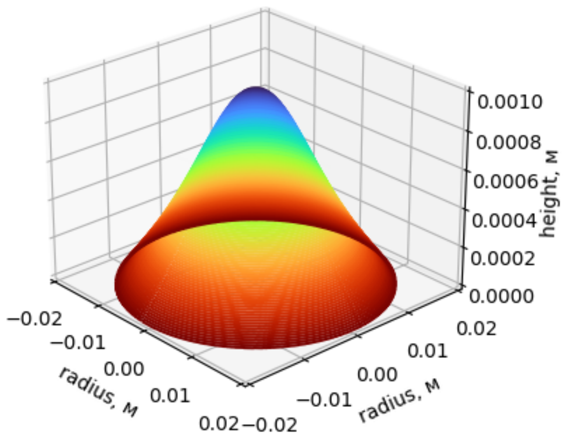

Figure 3: Disposition.

The computational model work results (Fig. 2 and 3) are demonstrate the maximum temperature of 474 C and the height deformation degree of the steel membrane at a given beam power level. It means that results are confirm the negative prediction of the assembly reliability under design conditions made in [1].

Asses

The calculation results errors estimation due to the joint influence of the uncertainties of the initial data is usually named the analysis of errors. First of all, the statistical characteristics of the initial data and the calculation parameters (mathematical expectations, variances and the relative standard deviations corresponding to these variances) need to be estimated or calculated. A series of systematic calculations of «critical» parameters need to then be carried out. The initial data for calculation serials are the values of the input parameters, the influence of the uncertainty of the assignment of which on the calculation result need to be determined.

It should be noted that the electron beam parameters (*I(τ)* on Fig. 4 and *E* on Fig. 5) and the outlet window membrane (*R, H*) have the most significant influence on the formation of the calculation error. After that the contribution of the uncertainty in setting the error of other initial parameters to the total calculation error (such as characteristics of the ventilation system and the environment) are evaluate.

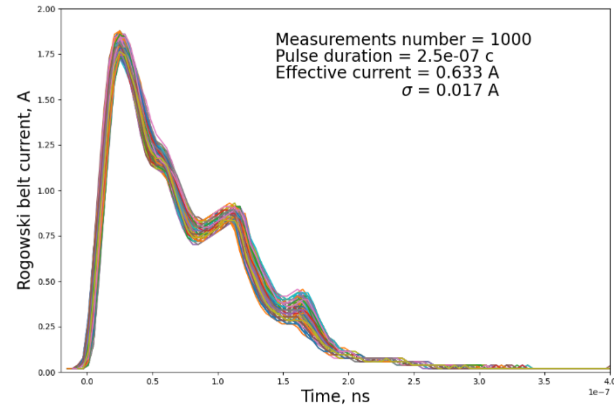

Figure 4: $I(\tau)$ – diagrams.

The presence of the energy release proportional dependence on the parameters of the electron beam and the membrane thickness is obvious. In fact, despite the fact that both input parameters are clearly included in the input data set for estimating energy release, there are no relationship between them. Nevertheless, the uncertainty in setting the energy release should be analyzed in a similar way and additionally determined the values of its inherent corresponding sensitivities. Thus, the desired value is characterized by the deviations of the beam parameters under the selected operating mode for the first case and by the quality of manufacture of the outlet window membrane, determined with a random error and a measuring instruments systematic error.

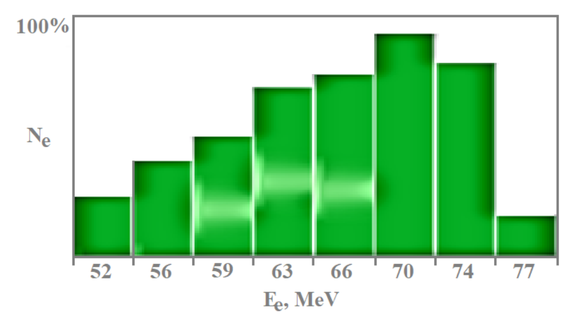

Figure 5: Energy spectrum of electrons.

From the results presented at the stage of the simulation follows that the «critical» parameters are the maximum temperature of the most heated membrane region $F_1 = T[max]$, and the mechanical stresses arising in the metal $F_2 = S[max]$. Thus, it is assumed in the work that the errors in determining the functional F_1 and F_2 the most significantly depend on *W, E, L, α, P*.

The sensitivity coefficients of the considered functional to changes in the initial parameters of the calculations were determined by sequentially varying one of them while maintaining the values corresponding to their mathematical expectations by other parameters. This is followed by a series of functional calculations with the initial data changed in this way. Then, the functional sensitivity coefficients to changes in the initial data in the point vicinity determined by the values of the mathematical expectations are numerically estimated. The evaluating results the sensitivity coefficients for the maximum temperature of the

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most heated outlet window membrane region (F_1) and the mechanical stresses arising in the metal (F_2) to a change in the initial calculation data are presented in a Table 1.

Table 1: Sensitivity Coefficients

Parameter name	$P_{T,i}$	$P_{U,i}$
Beam current	0.804	0.927
Electron energy	0.017	0.020
Membrane tick	0.456	-0.731
Press	0.000	0.135
Heat transfer	-0.280	-0.387

The uncertainties in setting the electron beam parameters are calculated by the results of the experimental data processing (Fig. 4). Foil thicknesses is regulated by industry standards. The analysis of the uncertainties in setting the initial data characterizing the ventilation system operation was carried out in accordance with the methodological recommendations [7], according to which deviations from the design data should not exceed 10% in terms of air flow (with a probability of 95%). The air pressure in the operation hall is formed due to the differences in the power of the supply and exhaust ventilation systems. That indicates the complete dependence of the uncertainty in setting this parameter on the uncertainty in setting the air flow rate. In the same way and for simplicity, we will take as an assumption the linear dependence of the heat transfer coefficient value (α) on the parameters of the ventilation system.

The RMS values (σ), characterizing the total errors in the functional calculation and introduced by the uncertainty of the initial data, were determined by the formula [8]:

$$\frac{\delta F}{F} = \sqrt[2]{\sum_{i=1}^{N}\left[\left(P_{Fi}\cdot\frac{\Delta i}{i}\right)^2\right]}. \tag{4}$$

The obtained values of the errors (σ) of the maximum temperature T of the most heated outlet window steel membrane region (F_1) and mechanical stresses arising in the metal (F_2) are 4.19% and 6.04%, respectively. Thus, the relative errors values in the determination of the «critical» parameters considered in the paper for the 95% confidence interval should be taken equal to 8.39% and 12.08%, respectively.

CONCLUSION

One of the numerous stages of substantiating the reliability of the design of the outlet window membrane of the LUE-200 accelerator has been carried out. A software has been developed that evaluates the membranes thermomechanical characteristics in continuous and pulsed operating modes. The features of the tool include tools for flexible customization of the solver and the ability to adapt the code for other tasks.

For the selected «critical» parameters, the sensitivity coefficients to the initial calculation data were calculated. As a result, the errors were calculated by evaluating the uncertainties of the beam current and electrons energy, the membrane geometry deviation during manufacture, and the operating characteristics of the supply and exhaust ventilation.

The obtained results have moderately high thermomechanical characteristics of the membrane assembly current configuration in operation at the maximum power level postulated in a paper. However, extreme caution should be exercised when operating the installation in such a parameters. The expected mechanical stress on the membrane is close to the ultimate strength of the material.

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