CW ELECTRON ACCELERATOR. RESONATOR COOLING EFFICIENCY AND THERMAL STRAIN COUPLED ANALYSIS PROCEDURE

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The procedure of the device under HF heating and turbulent liquid cooling displacement analysis by means of existent program code is presented. The spatial computational cell size and other requirements ensuring the needed computational accuracy are formulated. In order to illustrate the procedure developed an example analysis of the Electron Resonance Accelerator of a mean beam power up to 300 kW cooling efficiency and deformation is provided.

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INTRODUCTION

To accelerate electrons in the resonator of the accelerator developed by VNIIEF [1], proper electromagnetic oscillations with 100 MHz frequency are excited. Dissipative losses of high-frequency electromagnetic field (HF field) are related to induction of the high-frequency currents (HFC) in resonator walls. Under the action of currents the resonator walls are heated. This leads to displacement of the resonator case, violation of field distribution inside it, change of resonance frequency and decrease of Q-factor. Heat from the resonator walls is removed through washing of its outer surface by demineralized water flow pumped through the channels of the cooling jacket.

The described process is modeled by performing the coupled analysis cycle depicted in Fig.1.

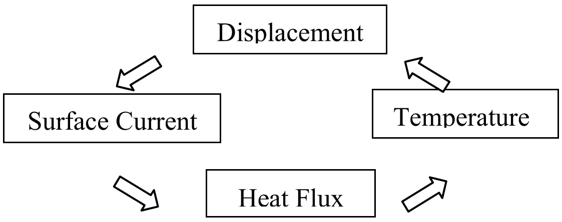

Fig.1. Coupled analysis cycle

Heat flux distribution is calculated from the current distribution known on the basis of electromagnetic (EM) analysis. Heat fluxes serve as loads in the thermal analysis. Temperatures calculated in the thermal analysis are transferred to the structural one. In the latter there are calculated coordinates of displaced geometry for the repeated EM analysis.

The proposed coupled analysis cycle is realized as a sequence of four calculation stages. Each stage is solved with the aid of common-purpose software available at VNIIEF.

At the first stage, a problem of high-frequency electromagnetic analysis of the accelerating structure is solved. The specific features of this calculation are presented in ref. [1].

At the stage of the thermal analysis the cooling channel distribution over the model surface is optimized and the required film coefficients are estimated. Temperature field in the structure is calculated.

During thermohydraulic analysis the parameters of cooling agent able to provide the required film coefficients are calculated.

In the structural analysis, the structure displacement due to its thermal expansion is determined.

1. THERMAL ANALYSIS

Within the bounds of thermal analysis the problem of steady-state heat conduction is solved by means of finite element technique. Heat fluxes of loss power serve as loads. Heat is removed through specifying the convection conditions for each cooled surface. In the course of a series of thermal analysis the film coefficients are selected. The goal is that the maximum temperature at any model point should not exceed the specified ultimate value T_{max}.

Heat fluxes are applied elementwise. The closest node of EM model is searched for each finite element of the heated surface. Basing upon the value of the surface current J in the node the mean heat flux per finite element is calculated:

$$q = K_2 K_3 K_4 J_\tau^2 \sqrt{\pi \rho f \mu}_{\,0} \qquad (1)$$

Here the factor K_2 averages the value of sinusoidal signal over time; K_3 takes into account resonator filling by radiofrequency power; K_4 is the loss power safety factor.

In order to check the adequacy of inter-model translation of the heat load total loss power on the whole application surface is calculated. In the case of its significant deviation from the value known from the EM analysis, the size of the finite element decreases, and the process of heat load application is repeated.

2. THERMOHYDRAULIC ANALYSIS

The averaged parameters of the cooling agent providing the film coefficients selected in the thermal analysis are preliminarily estimated with the aid of the known empirical relations. For short we will name this type of calculation “thermohydraulic analysis – method 1”. In the course of the calculation series, among others, the initial flow rate and temperature of cooling agent are determined. These values are used as the initial conditions for refined thermo-hydrodynamic check-up of the developed design.

Within the frames of the refined thermohydraulic analysis (“Method 2”) a thermo-hydrodynamic problem of the steady-state incompressible fluid flow is solved by the finite element technique. As a result of this solution temperature distribution in both solid and hydrodynamic model areas as well as pressures and velocities in the hydrodynamic area are determined.

The thermo-hydrodynamic problem is highly nonlinear one. As the applied software provides the first order finite element only for hydrodynamic problem solving, the accuracy of Nusselt number *Nu* computation is closely related to the discretization of the model boundary layer (Fig.2).

For the thermo-hydrodynamic analysis of the accelerator under development, discretization degree corresponding to *Nu* calculation accuracy not worse than 10% was selected.

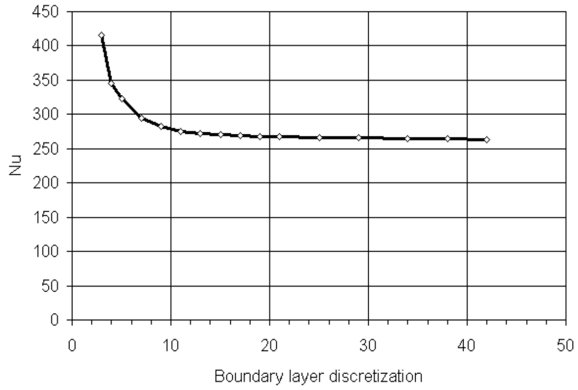

Fig.2. Influence of boundary layer thickness discretization on Nusselt number computation accuracy

Eddy viscosity of cooling agent is calculated using a turbulence model SST [2], allowing rather an accurate computation of *Nu* within a wide range of Reynolds numbers.

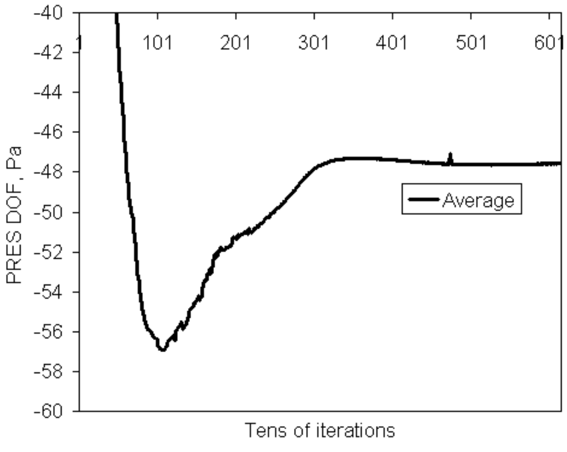

Fig.3. Oscillations of the absolute average values of degree of freedom PRES

Decision on hydrodynamic problem completion is taken basing upon the magnitude of oscillation of the absolute average values of the degrees of freedom (DOF) less than 1% (Fig.3).

3. STRUCTURAL ANALYSIS

Within the frames of the structural analysis the steady-state problem of thermal expansion is solved by the finite element technique. Nodal temperatures calculated in the thermal analysis serve as the loads at this stage. If necessary, additional loads, for example, ambient pressure, hydrodynamic pressure, gravity force etc. can be taken into account.

The field of displacements calculated from the structural analysis is output as a table and is available as initial geometry in the repeated EM analysis.

4. PROCEDURE APPLICATION

In conclusion, in order to illustrate the presented procedure application, let us present a typical computation of cooling efficiency and displacements of one of the variants of the developed accelerator case.

In this variant (Fig.4), the cooling agent (demineralized water) enters into the cooling jacket through the central pipe along the resonator axis and washes the case going through the annular cooling channel. Heat flux of the loss power is distributed along the resonator internal surface.

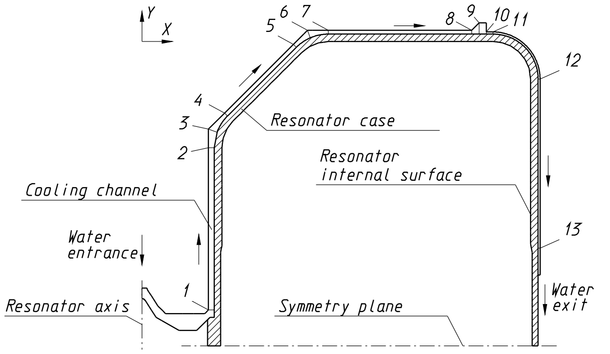

Fig.4. Resonator problem sketch

The heat load is calculated according to formula (1) and is shown in Fig.5 with arrows. Irregularity of heat load is almost four orders: the longest length of the arrow corresponds to the heat flux of about 80 kW/m^2 and the shortest one to that less than 14 W/m^2.

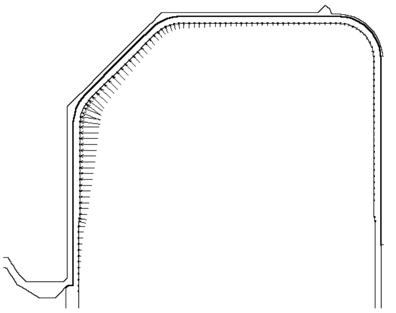

Fig.5. Heat flux distribution along the case

The analysis has been performed using the cooling agent flow rate of 100 l/min. Water temperature at the entrance was 15°C. Additionally, ambient pressure of 1 atmosphere was taken into account.

Calculation has shown that the cooling agent when passing the coolant loop will warm up by about 15°. The resonator case will warm up irregularly. The maximum temperature will reach ~135ºC on the inner case surface in the vicinity of cross-section 2 (Fig.4). The minimal temperature will be ~16ºC on the horizontal symmetry plane in the vicinity of the smaller radius of the case. In this case the maximal axial displacement of the case will be about 1.5 mm, the diametric one – about 0.9 mm. The water temperature in the thin boundary layer in the vicinity of cross-section 2 reaches the boiling-point.

Fig.6. Resonator case displacement

The pressure difference required to ensure the prescribed flow rate is about 0.04 atm. The character of the case displacement under the action of the HF field loss power and atmospheric pressure is shown in Fig.6.

CONCLUSION

A procedure of related Thermo-Hydro-Structural analysis of the accelerator being developed by VNIIEF is proposed. A technique for translation of the surface current distribution to the distribution of heat fluxes is proposed. The dependence of the calculation of *Nu* criterion on the degree of discretization of the thermo-hydraulic model boundary layer is found. To solve the developed accelerator problems, a discretization degree is selected that corresponds to accuracy of hydrodynamic computation no worse than 10%. It is suggested that the turbulence model SST should be used for calculation of induced cooling fluid viscosity. It is suggested that the decision on the hydrodynamic problem completion should be made when the absolute average degree of freedom oscillation is less than 1%. Using the proposed calculation cycle is demonstrated by a practical example of Thermo-Hydro-Structural analysis of the developed accelerator resonator case.

REFERENCES

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ЭЛЕКТРОННЫЙ УСКОРИТЕЛЬ НЕПРЕРЫВНОГО ДЕЙСТВИЯ. МЕТОДИКА ПОДГОТОВКИ ЗАДАНИЙ ПО РАСЧЕТУ ЭФФЕКТИВНОСТИ ОХЛАЖДЕНИЯ И ДЕФОРМАЦИИ РЕЗОНАТОРА

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Представлена методика подготовки заданий по расчету в существующих программных комплексах деформации конструкций, подверженных нагреву токами высокой частоты и охлаждению турбулентным течением жидкости. Определены требования к размеру пространственной счётной ячейки и другие условия, обеспечивающие необходимую точность расчётов. Приведен расчет эффективности охлаждения и деформаций корпуса электронного ускорителя непрерывного действия со средней мощностью пучка до 300 кВт, основанный на связанном анализе протекающих процессов и иллюстрирующий применение представленной методики.

ЕЛЕКТРОННИЙ ПРИСКОРЮВАЧ БЕЗПЕРЕРВНОЇ ДІЇ. МЕТОДИКА ПІДГОТОВКИ ЗАВДАНЬ ПО РОЗРАХУНКУ ЕФЕКТИВНОСТІ ОХОЛОДЖУВАННЯ ТА ДЕФОРМАЦІЇ РЕЗОНАТОРУ

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Представлено методику підготовки завдань по розрахунку в діючих програмних комплексах деформації конструкцій, що схильні до нагріву струмами високої частоти та охолодженню турбулентною течією рідини. Визначені вимоги щодо розміру просторової розрахункової комірки та інші умови, що гарантують потрібну точність розрахунку. Приведено розрахунок ефективності охолоджування та деформації корпусу електронного прискорювача безперервної дії з середньою потужністю пучка до 300 кВт, оснований на зв'язаному аналізу перебігу процесів та ілюструючий застосування представленої методики.