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Parametric analysis of space nuclear power plants in thermodynamic design variables

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Abstract

The purpose of the study is to analyze the influence of efficiency factor and medium-entropy temperatures on the specific mass of a space power plant and the specific area of the radiator cooler with regard for heat losses and mass coefficients of subsystems. Functions of the specific performance sensitivity to variations of design variables are used as the parametric analysis tool. It has been shown that sensitivity functions represent criteria relations that define the optimality and similarity range for space nuclear power plants (SNPP) of different types. To specify the permissible intervals for the variation of design variables, a form has been proposed for recording the specific characteristics with explicit interrelationships between target functions and design variables. The obtained results demonstrate a single-extremum dependence of the considered specific characteristics on generalized design variables. This makes it reasonable to define the optimization problem based on the said criteria of the SNPP technical level.

Keywords: Space nuclear power plants; Parametric analysis; Sensitivity functions; Technical-level criteria.

Introduction

A comparative analysis of different structures for space nuclear power plants (SNPP) is an essential stage in justification of design solutions [1–3]. Convenient comparison and optimization tools are target functions in the form of the "cost/effect" ratio. Such specific characteristics take into account both positive and negative factors and enable optimization and comparison of SNPPs of different designs and capacities to be performed in one scale [4].

As applied to the assessment of the SNPP technical level, the most important criteria nowadays are specific area of the radiator cooler (RC) per net capacity unit (SARC) and specific mass of power plant per net capacity unit (SMC). These target functions reflect both mass and dimension parameters of an SNPP and the energy conversion efficiency. The SMC and SARC therefore define to a great extent the capability for the launch of the plant into space using the existing delivery vehicles and the SNPP compliance with its designated purpose as a source of energy.

As part of the study, the SMC and SARC parametric analysis and optimization are considered in a space of thermodynamic parameters (specifically, efficiency factor and medium-entropy temperatures). These may be presented as generalized design variables (GDV). When doing this, one shall take into account the heat losses and mass coefficients of the SNPP subsystems, which makes it possible to update previous results [5,6] from estimation of thermodynamic effects on specific characteristics. The function of the specific performance sensitivity to variation of design variables is used as the tool for parametric analysis. It has been shown that sensitivity coefficients may be used as criteria relations that define the optimality and similarity domains for SNPPs of different types from the point of view of SARC and SMC.

It needs to be stressed that it is not enough for the designer to obtain a certain "optimum" point in the space of design

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variables. A proper justification of the design requires a great deal of information that describes the behavior of structures at different points within the domain D of permissible design variable values. Specifically, the designer needs to determine:

- the presence and distribution of extremums within the domain D;
- the cost of achieving the optimum from the base design point;
- the gradients and isograms of the design characteristics within the domain D.

As a rule, such information makes it possible to identify some of the new regularities in the behavior of target functions, that is, to update or simplify the calculation theory and techniques in the respective domain.

The problem of scanning the domain of design variables is traditionally solved through variant calculations. When the number of the considered points within the domain D is increased respectively and arranged in a particular way, a parametric analysis by way of variant calculations turns into an efficient algorithm for solving optimization problems by exhaustive search method [7,8]. And standard search algorithms used to find the global extremum turn out to be unnecessary, and so emphasis is placed on problems of choosing in an efficient way the respective points in the multidimensional domain D and presenting graphically the results of variant calculations based on computational experiment planning, e.g., using orthogonal central compositional planning [7,9]. In particular, certain functions – generalized design variables [7] associated explicitly or indirectly to the primary design variables through the product's geometry, dimensions and material composition parameters – are generated to reduce the problem dimensionality and limit the domain D. Each GDV point is matched by a particular domain of the variation of primary design variables. This hierarchy of design variables may contain several levels ensuring so that the dependences of target functions on design variables of different levels are detailed sequentially. The optimum points found at one level define the permissible domain for the search of the optimum at the level of detailing.

Specific characteristics of SNPPs and thermodynamic GDVs

The generalized design variables used in the study are represented by a series of thermodynamic parameters in the space of which SARC ($\varphi_c = F_c/N$, where F_c is the area of the RC radiating surface, and N is the net capacity) and SMC ($\gamma_{pp} = G_{pp}/N = G_{pp}(Q_h \cdot \eta)$), are analyzed parametrically where G_{pp} is the total SNPP mass, Q_h is the heater capacity, and η is the actual efficiency factor of the power plant). The adopted choice of design variables does not require the SNPP design and the thermodynamic cycle used to be updated, that is, makes it possible to obtain results which are valid for any SNPP types.

The efficiency of energy conversion will be characterized in more details if the intensity of heat losses Q_h is explicitly introduced and the expression for the actual efficiency factor is written in the form

$$\eta = 1 - (Q_h - Q_c - Q_l)/Q_h = \eta_t - \eta_l, \tag{1}$$

where $\eta_t = 1 - (Q_h - Q_c)/Q_h$ is the plant efficiency factor with no heat losses (thermal efficiency factor) taken into account; and $\eta_l = Q_l/Q_h$ is the fraction of heat losses. It also makes sense to introduce for consideration the *ideality coefficient* $k_{id} = 1 - \eta_l$ and the heat rejection ratio $r = Q_c/Q_h = 1 - \eta_t$. With $k_{id} = 1$, there are no heat losses in the power plant other than by heat removal in the thermodynamic cycle used. It is convenient to use ideality coefficient in parametric analysis problems since it is exactly what defines the interval of variations in the actual efficiency factor: $0 \le \eta \le k_{id}$.

We shall use medium-entropy values to characterize the cooler and heater temperatures:$T_c^{me} = Q_c/(s_1 - s_2)$ – medium-entropy temperature of the cooler;$T_h^{me} = Q_h/(s_1 - s_2)$ – medium-entropy temperature of the heater where $(s_1,\ s_2)$ is the interval of the entropy variation in the thermodynamic cycle used in the power plant. This leads to the expression of thermal efficiency factory through medium-entropy temperatures:

$$\eta_t = (Q_h - Q_c)/Q_h = \left(T_h^{me} - T_c^{me}\right)/T_h^{me}.$$

All of the values introduced above may be treated as generalized design variables. The interlinking between them makes it possible to introduce variables highlighting the regularities of a special interest (total SNPP efficiency, closeness of the real cycle to the ideal one, possibility for approximation to the Carnot efficiency, temperature dependences and other) as design variables.

Formally, mathematics permits the SMC and SARC minimum to be looked for relative to any of these variables, assuming that the other GDV values are constants or given the interlinking between them. Practically, however, achieving the optimum through the actual redesign of the structure seems to require exactly the GDV the variation of which may be expressed (taking into account the theory of processes taking place in the plant) in terms of the product dimensions, composition or shape to be selected as the varying design variable.

Standardization of target functions

Standardization of target functions suggests them to be given a form with explicit relationships of both target functions and design variables. This makes it possible to update the permissible intervals for the variation of variables. Thus, following a series of transformations, the SARC and the SMC are written in the form

$$\varphi_c = (k_{id}/\eta - 1)/E_c, \tag{2}$$

$$\gamma_{pp} = \varphi_c \cdot P_c + P_d/\eta, \tag{3}$$