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Conceptual Design Based on Scale Laws and Algorithms for Sub-critical Transmutation Reactors

Kwang Gu Lee and Soon Heung Chang

Department of Nuclear Engineering
Korea Advanced Institute of Science and Technology

ABSTRACT

In order to conduct the effective integration of computer-aided conceptual design for integrated nuclear power reactor, not only is a smooth information flow required, but also decision making for both conceptual design and construction process design must be synthesized. In addition to the aboves, the relations between the one step and another step and the methodologies to optimize the decision variables are verified, in this paper especially, that is, scaling laws and scaling criteria. In the respect with the running of the system, the integrated optimization process is proposed in which decisions concerning both conceptual design are simultaneously made. According to the proposed reactor types and power levels, an integrated optimization problems are formulated. This optimization is expressed as a multi-objective optimization problem. The algorithm for solving the problem is also presented. The proposed method is applied to designing a integrated sub-critical reactors.

1. INTRODUCTION

The design of nuclear power plants requires not only satisfaction of neutronics and hydraulics but also that of economics. That design need not to meet the technical factor but may meet just the economical factor. From the reasons like these the nuclear power plant is difficult to be designed in the detail. Thus development of conceptual design tool which can illustrate the trend of main parameters from key input is needed to achieve the detailed design.

The developed methodology principally employs the scaling laws and the algorithms. The Energy Amplifier are adopted as the reference reactors.

2. Design Methodology

2.1 Overall Evaluation Procedure

The reactor objectives of each type and the overall desirable design requirements should be considered to choose the optimum integrated reactors. Then the most appropriate reference reactor shall be adopted and the detailed design requirements and critical design criteria should be searched to establish the preceeding procedures. On basis of the design requirements of reference integrated reactors, the optimum system components shall be adopted. In addition, the reactor configurations shall be optimized and then the key design function and parameters are verified. These processes shall be achieved by the rule-based algorithmic processes, which is achieved by solution of the multiobjective problem matrices.

The preceeding procedures are consisting of the scaling objects. After these procedures shall be conducted, design basis accident (DBA) analysis should be validated to ensure the above design results. The DBA shall be checked here as the reactor vessel auxiliary cooling system (RVACS) performance of the Energy Amplifier.

2.2 Algorithmic Processes

The algorithmic process is started with the *design requirements*, which are initiated from the *reactor objectives*. The algorithms should be used to choose the reference power reactor, reference components and the other system, and to optimize or verify the main key parameters, including the reference design parameters.

The outputs of algorithmic processes shall be expressed as a multi-objective optimization problem which produces many optimization solution sets.

2.2.1 Outline of Algorithmic Process

The *decision-making items(DMI)* should be the items to be determined during the design processes. These should be constructed based on the following points.

- DMIs are determined such that the necessary conditions required for each DMIs are satisfied
- DMIs satisfying special requirements are determined in advance before executing the integrated optimization procedures
- DMIs for which it is hard to determine the relations with the 'evaluative characteristics' are established by using decision rules
- Systematic criteria are employed to determine DMIs

The defining evaluative characteristics at the step 2 should be determined, after the design requirements and the reactor objectives were chosen. The various evaluative characteristics are concerned for evaluating the reactor performance which shall meet the reactor requirements and the reactor objectives. So, to evaluate the evaluative characteristics, first the requirements and objectives should be determined according to the rule-based algorithms. Therefore, the evaluative characteristics are defined by the three items, that is I item, J item, and K item.

Each item is expressed as the follows;

- **I items** as the *DESIGN REQUIREMENTS*
- **J items** as the performance characteristics
- **K items** as the evaluative characteristics

Two assumptions are taken in this methodology; one is that the IHTS coolant is the same as primary coolant, and the other is that secondary system coolant is water.

From the aboves, the objective functions and the constraints should be determined. So, the objective functions are K_1 K_2 K_3 K_6 K_8. The remaining items must be evaluated as the constraints, that is, within the permissible region.

Then the necessary conditions in decision making should be evaluated at step 3. Because each DMI has the independent or dependent relationship to another DMI, the relationship should be so evaluated to verify the necessary conditions. At step 4, the preliminary determination of decision-making items will be achieved.

In this process, the monotone nature should be used to independently determine the DMIs. DMIs with no relationships with the evaluative characteristics can be determined prior to integrated optimization.

- If all of multiple objective functions, which are monotone with respect to any evaluative characteristics, that evaluative characteristics is definitely determined, thereby reducing the number of decision variables.

- The following rules are used for determining the DMIs.

(1) establishing the decision method

$$\text{If}\,[x = x_i] \quad \text{then}[\mathrm{U} = \mathrm{U}_{\mathrm{ij}}]$$

(2) established the specified value

$$\text{If}\,[\text{cond } i] \quad \text{then}[x_i = x_{io}]$$

where x denotes the DMI, x_I denotes the specified DMI, U denotes the decision method, and j denotes the jth decision method. Then the algorithmic process shall format an integrated optimization problems from the mapping diagram.

The objective functions and constraints determined by procedures up to step 3 are formulated as follows:

$$\text{Minimize } \psi = [e_1, e_2, e_3, ..., e_{u1}]$$

$$D_i^L \le D_i \le D_i^U$$

where i denotes the constraints of the evaluative characteristics. The design solutions are obtained by solving the above multi-objective optimization problems.

2.3 Scale Laws for Design Optimization

Scaling criteria for a natural and forced convection circulation are drived from the fluid balance equations, boundary conditions, and solid energy equations. On the present analysis, the scaling criteria developed by Ishii and Kataoka is used to obtain the preliminary conceptual design parameters for integrated reactors forced and natural circulation pool system under single- and two-phase flow conditions.

2.3.1 Similarity Parameters

The dimensionless variables and parameters used in the similarity study are obtained from the following dimensionless balance equations;

- *Single-Phase Flow*

Fluid continuity equation for ith section

$$U_i = U_r/A_i$$

Fluid momentum equation for flow path

$$\frac{dU_r}{d\tau}\sum_i L_i/A_i = RL_h(\theta_h - \theta_c) - \frac{U_r^2}{2}\sum_i (F_i/A_i^2) + F_d$$

Fluid energy equation for ith section :

$$\frac{\partial \theta_i}{\partial \tau} + (U_r/A_i)\frac{\partial \theta_i}{\partial Z_i} = (\theta_{si} - \theta_i)St_i$$

Solid structure energy equation for ith section :

$$\frac{\partial \theta_{si}}{\partial \tau} + T_i \nabla^2 \theta_{si} = Q_{si}$$

Fluid-Solid structure boundary condition for ith section .

$$\frac{\partial \theta_{si}}{\partial X_i} = B_i(\theta_{si} - \theta_i)$$

In the above equation, the fluid properties are assumed to be constant except for the buoyancy term, where the Boussinesq approximation is used.

- *Two-Phase Flow*

Mixture momentum equation

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial}{\partial z}(\rho_m u_m) = 0$$

Continuity equation for vapor

$$\frac{\partial \alpha \rho_g}{\partial t} + \frac{\partial}{\partial z}(\alpha \rho_g u_m) = \Gamma_g - \frac{\partial}{\partial z}\left(\frac{\alpha \rho_g \rho}{\rho_m} V_{gj}\right)$$

Mixture momentum equation

$$\frac{\partial \rho_m u_m}{\partial t} + \frac{\partial}{\partial z}(\rho_m u_m^2) = -\frac{\partial \rho_m}{\partial z} - \rho_m g - \frac{\partial}{\partial z}\left(\frac{\alpha \rho_g \rho}{(1-\alpha)\rho_m} V_{gj}^2\right) - \left(\frac{f_m}{2D} + \frac{K}{2}\delta(z - z_i).\right)\rho_m u_m |u_m| + F_d$$

Mixture enthalpy energy equation (ith section)

$$\frac{\partial \rho_m H_m}{\partial t} + \frac{\partial}{\partial z}(\rho_m u_m H_m) = \frac{4h_m}{d}(T_s - T_{sat}) - \frac{\partial}{\partial z}\left(\frac{\alpha \rho_g \rho}{\rho_m} \Delta H_{fg} V_{gj}\right)$$

Solid energy equation (ith section)

$$\rho_s C_{ps} \frac{\partial T_s}{\partial t} + k_s \nabla^2 T_s - \dot{q}_s = 0$$

where the parameters are the same as the case of single-phase flow.

These governing equations are rearranged in dimensionless forms in both case of single and two phase flow conditions:

2.3.2 *Similarity Laws*

From the dimensionless form of differential equations it is evident that if the similarity is to be achieved between processes observed in a model and in the prototype, it is necessary to satisfy the physical and geometric similarities.

In addition, for simplicity this design process should use the same material for structures and the same working fluid with the same operating conditions, i.e. with the same system pressure, are assumed in the present analysis.

In contrast with the hydrodynamic similarity the thermodynamic similarity is difficult and deeply related with a flow field and fluid properties. So, the additional constraints on the flow field are needed. In general, the heat transfer coefficient depends on the fluid properties and flow conditions.

3. Results and Validation

The reactor configuration of long-lived radio-nuclide transmutation reactor (600MWe) was defined by the this system. The main characteristics are like the follows:

- Elimination of IHTS
- (New) Straight type S/G tube ; 4 S/G
- Reduction of the ratio of plant area to depth
- Heat removal at primary system by natural convection
- Use of metal fuel and Pb-Bi as coolant and target material

Fig. 2 is the reactor configuration of the long-lived radio-nuclide transmutation and Fig. 3 is the detailed core geometry and the configuration.

The reactor vessel configuration has the following characteristics:

- 412 assemblies
- U-18Pu-8MA-10Zr metallic fuel
- FP alloy in noble FP canister or FP alloy in noble FP metallic matrix

In addition, the optimized design parameters of each reactor were verified by the scale laws and the design validation codes. Tables 1 are the optimized design parameters and the similarity quantities of the integrated LMR, the integrated PWR, and the integrated sub-critical reactor.

The optimized design parameters and the optimized reactor were validated by the COMMIX code with the decay heat removal of the RVACS. The Fig. 4-5 are the validation results of the integrated sub-critical transmutation reactor.

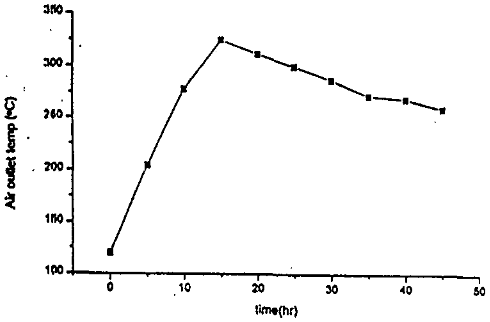

Fig. 4 Air mass flow rates

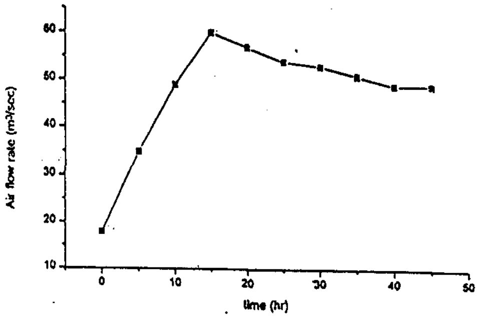

Fig. 5 Air outlet temperature

From the above results, it is obvious that the RVACS of the reactor shall effectively move the residual heat after the scram.

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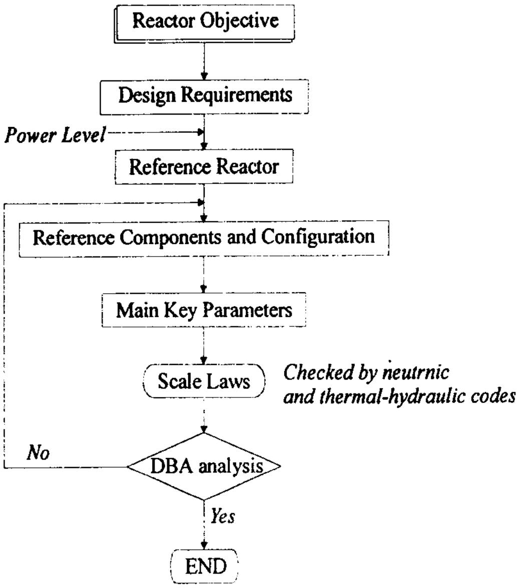

Fig. 1 Overall evaluation procedure for design optimization

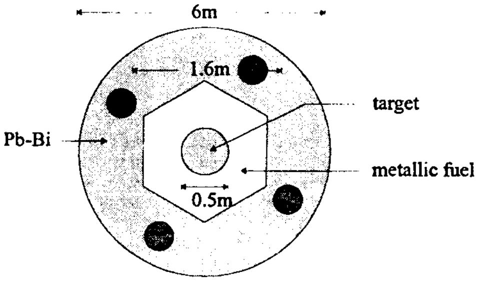

Fig. 3 Core configuration of sub-critical reactors

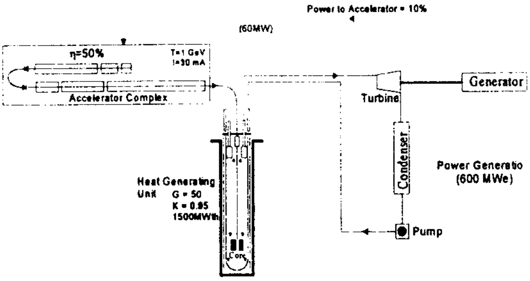

Fig. 2 Sub-critical transmutation reactor

Table 1 Long-lived radio-nuclide transmutation reactor (600MWe)

Component	Items	M/P ratio	Design Parameters
core	equivalent diameter (cm)	$a_R^{1/2}$	160.0
	height (cm)	l_R	293.7
Reactor Vessel	core inlet temperature (°C)	$\Delta T_R = 1$	397
	core outlet temperature (°C)		595
	equivalent diameter (cm)	$a_R^{1/2} \times l_R$	596.0
	height (cm)	$a_R^{1/2} \times l_R$	3110
	S/G inlet hole (cm)	$a_R^{1/2} \times l_R$	2450
	sodium level (cm)	$a_R^{1/2} \times l_R$	2698
Containment Vessel Gap Size (cm)		$a_R^{1/2} / l_R$	19.5
RVACS	riser gap size (cm) = x_R		17.7
	downcomer gap size (cm)		58.2
S/G	type		Superheated steam
	Throttle condition (psig/°C)		2200/520
	Heat transfer capacity (MW)	$a_R l_R$	375 (4 #)
	Heat transfer area (m^2)	$a_R l_R^{0.8}$	2480
	# of tubes per a S/G	$a_R l_R^{-0.2}$	3980
	S/G height (m)	$a_R^{1/2} l_R^{-0.1}$	8.43
	tube length (mm)	l_R	980