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# Axiomatic Design Approach for the advanced GT-MHR core

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## 1. Introduction

System design is generally depends on the designer's knowledge and know-how. Improving one function may cause deteriorating another function without designer's conscious. Each functional component affects each other in general design. This is due to complexity: complexity is defined as a measure of uncertainty in achieving the specified functional requirements. By the Axiomatic design approach, systems can be minimized its complexity and perform better.

This method is employed to design the HTGR core in this study. Therefore, the purpose is to optimize the value of design parameters.

## 2. Method

Axiomatic design has been suggested to methodically design systems [1], and the kernel of it consists of two axioms to guide the better performed design, as follows:

- Independence axiom
  Maintain the independence of the functional requirements.
- Information axiom
  Minimize the information content of a design.

At present, the whole mechanical HTGR systems have not been set up yet, and the information of each component can not be gathered. Based on only the Independence axiom, not the Information axiom, the system will be evaluated here.

The procedure of the axiomatic design approach is the sequence of decomposing system, characterizing system, populating design matrix, evaluating system, and optimizing system in final.

### 2.1 Decomposing system

Zigzagging process is used to decompose the existing HTGR core, especially GT-MHR as the reference here. The decomposed hierarchies consist of the functional requirement (FR) in functional domain and the design parameter (DP) in the physical domain, and the mapping between FR and DPs should obey the first axiom at each level. It is shown in Figure 1.

### 2.2 Characterizing system

Conceptualization process occurs during the mapping process going from the functional domain to the physical domain. To go from WHAT to HOW requires the system analysis. Characterizing the system must be modeled first for populating the design matrix and the general governing mathematic equations are contracted as follow:

- Mass

$$u = \frac{\dot{m}}{A\rho}$$

- Momentum

$$\frac{dP}{dz} = \rho u^2\left(-\frac{1}{T}\frac{dT}{dz} + \frac{1}{P}\frac{dP}{dz}\right) - \frac{4f}{D_e}\cdot\frac{\rho u^2}{2} - \left(\left(K_{ent} + K_{orf}\right)\frac{\rho u^2}{2}\delta(0) + K_{exit}\frac{\rho u^2}{2}\delta(L)\right) + \rho g$$

- Energy

$$\rho u\left(c_p\frac{dT}{dz} - \frac{1}{\rho}\frac{dP}{dz}\right) = \dot{Q}''' + 2\mu\left(\frac{du}{dz}\right)^2$$

When the equations are solved, then the relationship between FRs and DPs can be elicited and it can make out to complete the design matrix. The design values for GT-MHR were referred to the previous study [2].

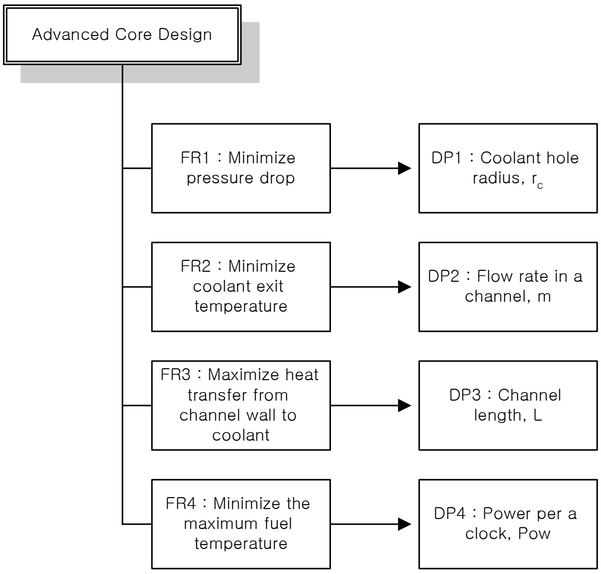

**Figure 1. The Hierarchy of FRs and DPs for core design**

### 2.3 matrix mapping

Mapping process between the domains can be expressed mathematically in terms of the characteristic vectors that define the design goals and design solutions.

$$\begin{bmatrix} \Delta(\Delta P) \\ \Delta\left(T_{c,\max}\right) \\ \Delta\left(T_{w,\max}\right) \\ \Delta\left(T_{f,\max}\right) \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{44} & A_{44} \end{bmatrix} \cdot \begin{bmatrix} \Delta r_c \\ \Delta\dot{m} \\ \Delta L \\ \Delta Pow \end{bmatrix}$$

where, $A_{ij} = \frac{\partial FR_i}{\partial DP_j}$

Because of the non-linearity, the elements of the design matrix may vary, depending on the specific values of DPs, so that the design behaves as a coupled, uncoupled, or decoupled design.

2.4 Evaluating system with R/S analysis

When $\mathrm{DP}_i$ only changes, $\mathrm{FR}_i$ and $\mathrm{FR}_j$ simultaneously changed. The quantity of change can be calculated by introducing the concept of Reangularity (R) and Semangularity (S), which are defined as:

$$R = \prod_{\substack{i=1,n-1 \\ j=i+1,n}} \left( 1 - \frac{\left( \sum_{k=1}^{n} A_{ki} A_{kj} \right)^2}{\left( \sum_{k=1}^{n} A_{ki}^2 \right)\left( \sum_{k=1}^{n} A_{kj}^2 \right)} \right)^{1/2} \qquad S = \prod_{j=1}^{n} \left( \frac{\left| A_{jj} \right|}{\left( \sum_{k=1}^{n} A_{kj}^2 \right)^{1/2}} \right)$$

If the design matrix is uncoupled, R and S equal unity. If the design matrix is decoupled, R and S are equal, but not unity and when the matrix is coupled. The closer the values of R and S, and the closer each is to a value of 1.0, the better the system.

Decoupleness (DC) and Uncoupleness (UC) were defined in this study to judge the degree of decoupling as follow:

$$DC = 1 - \frac{|R - S|}{R + S} \qquad UC = \sqrt{\frac{R^2 + S^2}{2}}$$

The criterion to decide the degree of uncoupling between FRs and DPs is like:

$$\delta FR_i \geq \sum_{\substack{j \neq i \\ j=1}}^{n} \frac{\partial FR_i}{\partial DP_j} \Delta DP_j$$

## 3. Results & Discussion

Based on the given present GT-MHR design value, the design matrix was calculated like:

$$\begin{bmatrix} \Delta(\Delta P) \\ \Delta(T_{c,\max}) \\ \Delta(T_{w,\max}) \\ \Delta(T_{f,\max}) \end{bmatrix} = \begin{bmatrix} 2.186\times10^{7} & -2.884\times10^{6} & -80.71 & -4.143\times10^{-4} \\ 0 & -1.244\times10^{4} & 0 & 6.143\times10^{-5} \\ 2798 & -1.257\times10^{4} & -3.502 & 6.301\times10^{-5} \\ -1507 & -1.218\times10^{4} & -19.99 & 7.720\times10^{-5} \end{bmatrix} \cdot \begin{bmatrix} \Delta r_c \\ \Delta \dot{m} \\ \Delta L \\ \Delta Pow \end{bmatrix}$$

R, S, DC and UC were as follow:

$$\begin{bmatrix} r_c \\ \dot{m} \\ L \\ Pow \end{bmatrix} = \begin{bmatrix} 7.94\ mm \\ 320\ kg/s \\ 7.93\ m \\ 600\ MW \end{bmatrix} \rightarrow \begin{bmatrix} \Delta P \\ T_{c,\max} \\ T_{w,\max} \\ T_{f,\max} \end{bmatrix} = \begin{bmatrix} -42934 \\ 851.2 \\ 860.6 \\ 946.4 \end{bmatrix} \Rightarrow \begin{bmatrix} R \\ S \\ DC \\ UC \end{bmatrix} = \begin{bmatrix} 1.532\times10^{-5} \\ 3.234\times10^{-5} \\ 0.6403 \\ 2.543\times10^{-5} \end{bmatrix}$$

According to the results and the criterion for decoupling, the current design seems the decoupled system.

$$\begin{bmatrix} \Delta P \\ T_{c,\max} \\ T_{w,\max} \\ T_{f,\max} \end{bmatrix} = \begin{bmatrix} X & O & O & O \\ O & X & O & O \\ X & X & X & O \\ X & X & X & X \end{bmatrix} \cdot \begin{bmatrix} r_c \\ \dot{m} \\ L \\ Pow \end{bmatrix}$$

However, no one can determine whether the decoupling system is superior to the uncoupling system. Now the question is to reduce the degree of decoupling among the decoupled condition.

The amount of variation of current design values is restricted. The constraints are like:

- Length$\leq$ 8.723m
- Power$\leq$ 690MW
- Pitch between channels >0.00361m

Satisfying the constraints for each DPs, the decoupleness can be minimized. The decoupleness at each design case is summarized in Table 1.

The case 1 is for the current condition. However, the case 2 is the wholly decoupled design and thus should be selected in axiomatic view. The possibility of power up-rating is the meaningful result as well.

## 4. Conclusion

The design in a physical level is naturally coupled due to characteristics of thermal-fluid systems. Although parts of the system are naturally coupled, reducing the degree of coupling can be made by the axiomatic design principles.

By the axiomatic design approach, the advanced fuel assembly design is suggested, and its performance is enhanced as well.

## ACKNOWLEDGMENT

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## REFERENCES

[1] N.P. Suh, Axiomatic Design: Advances and Applications. Oxford University Press, New York, USA, 2001.

[2] Syd Ball, Sensitivity Studies of Modular High-Temperature Gas-Cooled Reactor (MHTGR) Postulated Accidents, 2nd International Topical Meeting on HTR Technology, 2004.

**Table 1. The degree of decoupling for the change of design parameters**

| Case# | No. of Channel per block | Coolant radius [mm] | Flow rate [kg/s] | Length [m] | **Power [MW]** | **$T_f$ [℃]** | **Decoupleness** |
|---|---|---|---|---|---|---|---|
| 1 | 108 | 7.94 | 320 | 7.930 | **600** | **946.4** | **0.6403** |
| 2 | | 8.54 | 320 | 8.723 | **630** | **953.7** | **1.0000** |
| 3 | | 8.84 | 371.2 | 7.930 | **640** | **923.3** | **0.9495** |
| 4 | | 8.84 | 371.2 | 8.723 | **690** | **941.1** | **0.8626** |