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Evaluation Metrics for Intermediate Heat Exchangers for Next Generation Nuclear Reactors

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INTRODUCTION

The Department of Energy (DOE) is working with industry to develop a next generation, high-temperature gas-cooled reactor (HTGR) as a part of the effort to supply the United States with abundant, clean, and secure energy as initiated by the *Energy Policy Act of 2005* (EPAct; Public Law 109–58,2005) [1]. The first of a kind HTGR envisioned for the NGNP is an extension of past applications of gas-cooled reactor technologies and will be driven by near-term commercial industry needs and current technology availability. The next generation nuclear reactors (NGNR) such as HTGR, Fluoride High Temperature Reactor (FHR) are intended to increase energy efficiency in the production of electricity and/or provide high temperature heat for industrial processes. The efficient transfer of energy for industrial applications depends on the ability to incorporate effective heat exchangers between the nuclear heat transport system and the industrial process heat transport system. However; the need for efficiency, compactness, and safety challenge the boundaries of existing heat exchanger technology, giving rise to this study, which evaluates the criteria for evaluating heat exchanger performance. Potential heat exchanger configurations or designs description (such as printed circuit, spiral or helical coiled, ceramic, plate and fin, and plate type) are beyond the scope of this study. This study mainly focuses on the criteria which will be utilized for evaluation of the proposed designs. Figure 1 presents a selection framework for heat exchanger selection and design which is dependent on the condition and environment of the application.

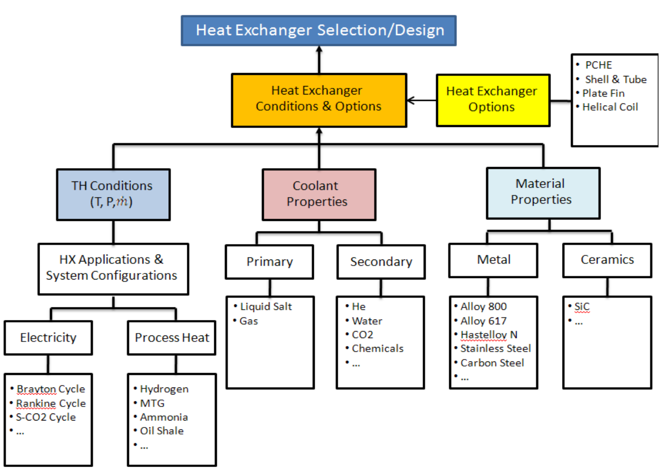

Figure1. Heat Exchanger Selection Framework

EVALUATION METRICS

There are many variables to be evaluated in the selection of a particular type of heat exchanger for a given application. This section presents the major characteristics that help in evaluation of a heat exchanger.

Thermal-Hydraulic Performance

Thermal performance is the primary criterion for most of the heat exchanger selection process. Heat transfer performance, effectiveness and fouling were considered as major thermal performance factors. For higher heat transfer performance, the heat exchanger requires higher heat transfer coefficient and less pumping power [2]. High effectiveness is important because it can provide thermal energy with less exergy loss, resulting in higher thermodynamic efficiency. Fouling is also an important factor because it significantly degrades thermal performance of the heat exchanger (especially for liquid coolants).

Structural Performance (Mechanical Integrity Characteristic)

Heat exchanger integrity can be categorized primarily by how it operates under steady-state and transient conditions. Heat exchangers are exposed mainly to two different stresses: (1) mechanical stress and (2) thermal stress. Vibration is also important heat exchanger criteria because it could degrade the integrity of the heat exchanger. Validating the effects of system pressure and temperature on the integrity of the joints (diffusion bonding, brazing, and welding) under steady-state and transient conditions is necessary and would enable a better selection of the heat exchanger. Bonds are subjected to static and dynamic loading while the heat exchanger is operating; the one with better performance will be ranked higher. The materials being considered for the heat exchanger (alloys 617, 230, 800H and Hastelloy N for FHR) all spontaneously form chromium rich oxide scales, which present problem in making diffusion bonds. The diffusion bonding process needs to be further developed and bonding process parameters and controls identified. Creep data at high temperatures will be needed for the selected material in order to develop creep-fatigue interaction diagram.

Corrosion

A factor in the lifetime of a heat exchanger will be its resistance to corrosion in the operating environment.

Corrosion resistance will be a function of the materials of construction, as well as the thickness of various sections. If the selected material cannot effectively prevent corrosion, a better or a preferred option will be for the heat exchanger to have thicker walls (more forgiving) and more corrosion allowance incorporated into the design.

Technology Readiness

Technology Readiness is an important criterion for heat exchanger selection. A technology may look promising but still need to be demonstrated under the operating conditions and environment.

Tritium Permeation

Tritium is mainly generated in the reactor core by ternary fissions and various neutron reactions. It is easily permeated through the high temperature metallic surfaces. Since tritium is radioactive isotope, it can contaminate the industrial system and products, eventually. For mitigating tritium permeation, less heat transfer surface area and larger heat exchanger thickness are preferred in the design.

Inspection

Inspection should be easily accomplished to determine the state of the equipment. Compact heat exchangers, being small units, are not easy to inspect. A heat exchanger designed so that joints can be examined and cracks and crack growth identified more easily over its operational lifetime is preferred. Nondestructive evaluation (such as Eddy Current Testing, Ultrasonic Testing, Radiography, and Pressure Leak Testing) may be used to evaluate the structural integrity of heat exchanger components.

Maintenance

The ease of maintenance, such as cleaning, repair, and serviceability, is an important characteristic for a successful heat exchanger. All heat exchangers should be chemically cleanable, which is more effective and efficient than dismantling and physically cleaning them. The heat exchanger should also have provision for replacing any components subject to corrosion, unless it is more economical to replace the whole unit [3]. Thus, a heat exchanger with these capabilities is preferred.

Life Cycle Costs

In one respect, the life-cycle cost for a given heat exchanger can serve as a single criterion for comparison. Such aspects as development, design, fabrication, installation, and maintenance costs can be included in the life-cycle cost. However, at this point, the heat exchanger concepts are not sufficiently developed to provide accurate cost information on which to base these comparisons. Therefore, the cost comparisons will be qualitatively addressed.

EVALUATION MEHODOLOGY

After understanding different criteria's in the evaluation metrics, analytical hierarchy process (AHP) is used to compare candidate heat exchangers. AHP provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions [4]. AHP enables decision-makers to derive ratio scale priorities or weights as opposed to arbitrary assigning values. The procedure for using AHP can be summarized as [5, 6,7]:

1. Model the problem as a hierarchy containing the decision goal, the alternatives for reaching it, and the criteria for evaluating the alternatives.
2. Establish priorities among the elements of the hierarchy by making a series of judgments based on pairwise comparisons of the elements.
3. Synthesize these judgments to yield a set of overall priorities for the hierarchy.
4. Check the consistency of the judgments.
5. Come to a final decision based on the results of this process.

This section summarizes the preliminary evaluation results for the heat exchanger selection conducted by AHP. Because of lack of experimental information, the decisions were based on qualitative information and inference. In this case, two potential (Shell and Tube, Printed Circuit Heat Exchanger) heat exchangers are compared using AHP, as shown in Figure 2.

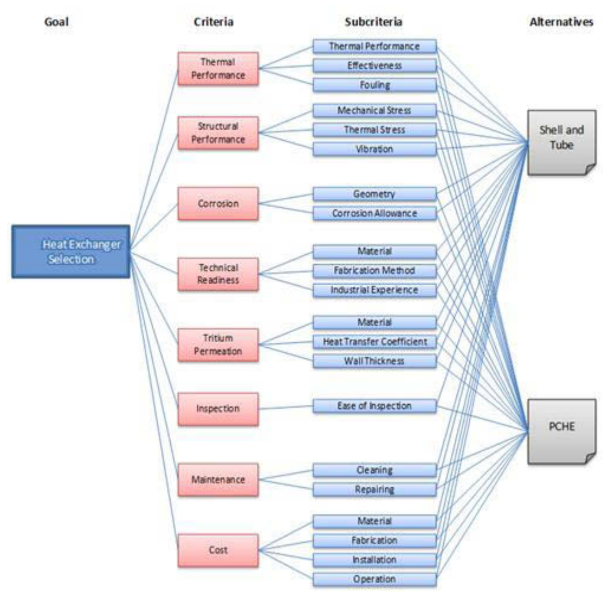

Figure2. Decision Hierarchy for Heat Exchanger Selection.

Based on scores and weights obtained from pair wise comparisons, final priorities of the alternatives were evaluated with respect to the goal as shown in Figure 3.

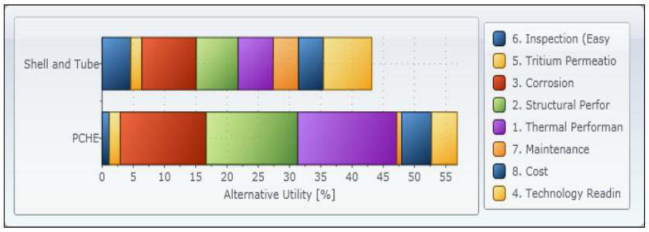

Figure3. Ranking of Heat Exchanger Based on Evaluation Criteria

The following summarizes the results:

- **Thermal Performance**: PCHE exchangers have better heat transfer performance and effectiveness contributed from their compactness compared to the shell-and-tube heat exchanger.
- **Structural Performance**: PCHE exchangers have better performance for the mechanical stress because of their unique bonding methods (diffusion bonding). Relatively larger thickness-to-diameter ratios of the PCHE are preferred for better mechanical stress. PCHE are prone to less vibration than the shell-and-tube heat exchanger that consists of lots of flow tubes.
- **Corrosion Performance**: PCHE heat exchangers have smaller heat transfer wall thickness than the shell-and-tube heat exchanger. This design is better for the thermal performance, but not preferable in the corrosion environment. In the material perspectives, PCHE generally uses a single material for construction while the shell-and-tube heat exchanger consists of several materials for different sections.
- **Technology Readiness**: The shell-and-tube heat exchanger has much higher technical readiness level compared to the PCHE.
- **Tritium Permeation**: The PCHE have smaller heat transfer area than the shell-and-tube heat exchanger, which is preferable characteristic for reducing tritium permeation. However, they have smaller wall thicknesses, which is not preferred.
- **Inspection**: The Shell-and-tube are much better in inspection compared to the PCHE, mainly because of ease of access.
- **Maintenance**: The Shell-and-tube are much better in maintenance for both cleaning and repairing compared to the PCHE. Both physical and chemical cleaning are available for the shell-and-tube heat exchanger while PCHE only allows chemical cleaning.
- **Life Cycle Costs**: The Shell-and-tube heat exchanger provides less fabrication and operation & maintenance cost. However, it will require more material cost and installation cost because of its larger size. In this study, cost was included in the evaluations. However, in the complex decisions, the AHP usually sets the cost aside until the benefits of the alternatives are evaluated.

CONCLUSIONS

In order to select the optimum heat exchanger the evaluation criteria, trade-off factors, and estimated life-cycle costs discussed in this study should be analyzed. The optimum designs are those that meet the most performance requirements at the minimum life-cycle cost. This study used analytical hierarchy process for evaluation of the candidate heat exchangers. For this evaluation, 8 criteria and 21 sub criteria were selected and organized as a hierarchy structure. In this analysis, the inconsistency factors of all the weighting and ratings were reduced below 10%, which is recommended in the AHP methodology. The evaluation matrix and results will be further improved as the technology matures and there is more availability of experimental data.

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