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Design of Nanoparticle Engineered Safety Injection Tank

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1. Introduction

Nanofluids, which are engineered colloidal suspensions of nanoparticles in a solvent have been found to show significantly enhanced coolant properties with respect to other fluids, due to higher critical heat flux and surface wettability at modest nanoparticle concentrations [1]. In order to bring these benefits to nuclear power plants, attempts to improve the performance of safety features such as emergency core cooling systems (ECCSs) are being made in laboratory environments. This study proposes a design process to reform a previous design of nanofluid-assisted ECCS using Axiomatic Design (AD) principles and TRIZ.

2. Methods and Results

2.1 Axiomatic Design & TRIZ

The purpose of AD is to facilitate the improved design of various tangible and intangible products. It provides an objective means for evaluating competing designs and enabling the best design to be chosen. According to one of the axioms, called as independence axiom, designers should maintain the independence of the design goals. The mapping process between the domains can be explained mathematically in terms of characteristic vectors that define the design goals (FRs) and design solutions (DPs):

$$\{FR\} = [A]\{DP\}$$

where, [A] is the design matrix that helps designers to mathematically apply the independence axiom[2].

TRIZ is a knowledge-based methodology for facilitating problem-solving in the context of invention. There are three steps in the application of TRIZ to AD: Abstractizing contradictions from AD, decoupling the contradictions and concretizing the decoupled design. We conformed to these procedures for this study.

2.2 Reverse Engineering of Conventional Ideas

For the reverse engineering of the previous ECCSs, we must first consider the top FR and DP, as follows [3];

FR0: shut down a reactor while preventing core melt after LOCA
DP0: nanofluid-engineered ECCS

The sub-FRs of DP0 are the requirements to inject coolant during the initial phase (FR1) and to provide long-term cooling (FR2). The respective DPs of FR1 and FR2 constitute the safety injection system and shutdown cooling system. We completed the set of FRs and DPs corresponding to the previous method, namely, the preloading of nanoparticles into a conventional safety injection tank (SIT). Figure 1 shows that the coupling is attributed to the method. The boxes marked indicate that the contradictions do not satisfy the functions simultaneously.

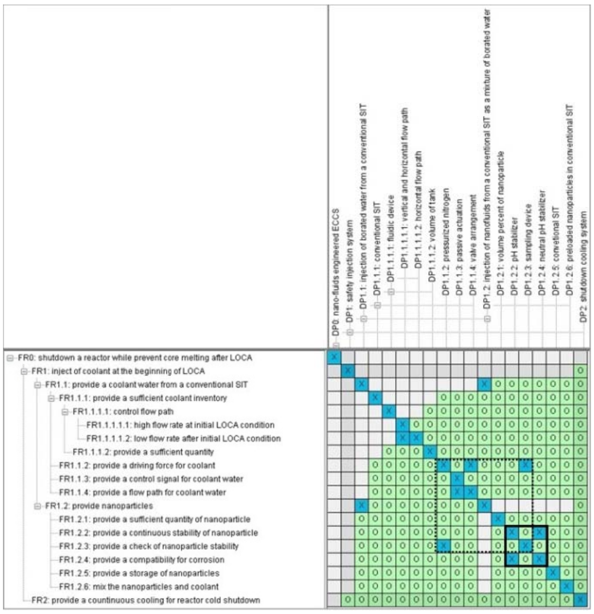

Figure 1. Design matrix of applications of nanofluids in ECCSs [4]

Two important couplings are identified. The first coupling is as follows.

The coupling caused by sampling of nanoparticles and pressurized nitrogen.

$$\begin{bmatrix} \mathbf{FR1.1.2} \\ \mathbf{FR1.2.3} \end{bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \begin{bmatrix} \mathbf{DP1.1.2} \\ \mathbf{DP1.2.3} \end{bmatrix}$$

FR1.1.2: provide a driving force for the nanoparticles
FR1.2.3: provide a check for nanoparticle stability
DP1.1.2: pressurized nitrogen
DP1.2.3: sampling device

The sampling for checking the stability of nanoparticles requires depressurization of the contents of the SIT. However, the depressurization of the SIT does not contribute to a driving force for the coolant water and nanoparticles.

The coupling caused by a low pH for the stability of nanoparticles and a neutral pH for corrosion prevention.

$$\begin{bmatrix} \mathbf{FR1.1.2} \\ \mathbf{FR1.2.3} \end{bmatrix} = \begin{bmatrix} \mathbf{X} & \mathbf{X} \\ \mathbf{X} & \mathbf{X} \end{bmatrix} \begin{bmatrix} \mathbf{DP1.1.2} \\ \mathbf{DP1.2.3} \end{bmatrix}$$

FR1.2.2: provide stability of nanoparticles
FR1.2.4: provide compatibility for corrosion resistance
DP1.2.2: pH stabilizer (acidic condition)
DP1.2.4: neutral pH stabilizer

To ensure homogeneity of the nanoparticles in the SIT, the pH state of the SIT should be acidic. However, acidic contents can induce corrosion of the SIT.

2.3 New Design through the Decoupling Process

Using the "inventive principles" provided by TRIZ tools, we redesigned conventional nanoparticle injection systems.

For the first coupling, we used TRIZ theory to solve the contradiction "high pressure, but also atmospheric pressure" with a contradiction matrix. This matrix provides selective options for "features to improve" and "undesired results". We abstractized the former problem as "the difficulty of detection and measurement for the feature to be improved and the form of the undesired result". We can consider the use of another tank connected to the conventional SIT for nanoparticle storage and injection based on this procedure. To solve the second coupling's contradiction "low pH, but also neutral pH", we abstractized the feature to improve for stability of objection's composition and the undesired result for object-affected harmful factors. Consequently, we could decide to use a titanium coating to enhance the corrosion resistance of the interior of a tank preloaded with nanoparticles; this corresponds to the concretization process. As a result, this paper proposes a nanoparticle injection tank for the convenient sampling and injection of nanoparticles, as shown in Fig. 2.

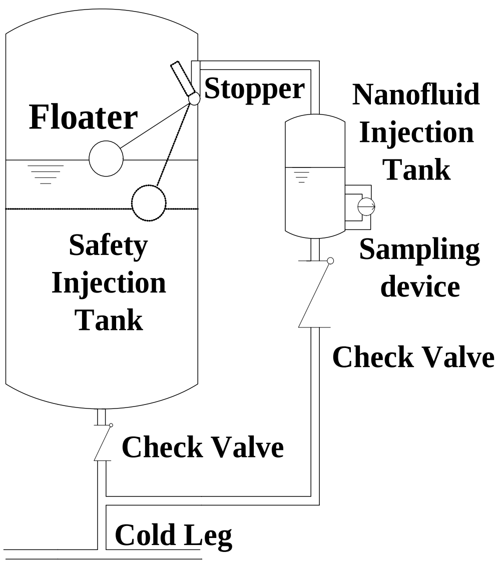

Figure 2. Nanoparticle-engineered SIT

This device consists of a coolant storage component and a nanofluids storage component. The coolant storage component can sustain not only a pressure of 40 bar, but also a neutral pH state. On the other hand, the nanofluids storage component can maintain its contents at atmospheric pressure, while also maintaining them at a stable low pH with a titanium coating on the inner surface of the tank. As shown in Figure 2, during normal operation, the nanoparticle storage component and borated water coolant storage component are separated by an isolation stopper connected to a heavy material floater inside the SIT. Following a LOCA, the pressure inside the reactor coolant system (RCS) decreases below the pressure of SIT, at which point emergency coolant is injected into the RCS. At this moment, the force generated by the floater opens the isolation stopper. Finally, the pressurized nitrogen causes the nanoparticles, mixed with coolant water, to be injected.

3. Conclusions

Following an analysis of conventional ideas, major couplings were recognized, such as stored nanoparticle sampling and chemical compatibility. To solve these kinds of couplings, the installation of an additional storage tank adjacent to the SIT was proposed. While this paper did not present a detailed solution confirmed by experiment or code analysis, it focused on explaining which design process was more efficient in terms of reflecting axioms of the engineering system, and showed how to create nanofluid injection systems as an illustrative example.

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