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A Design Study for Standard Nanofluid Coolants

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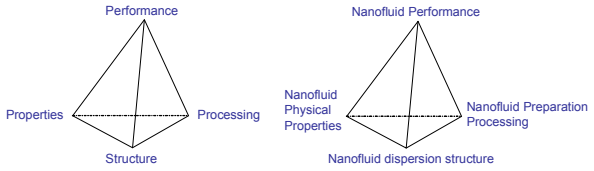
1. Introduction

The experimental data for nanofluids in thermal-fluid systems have shown that the new fluids promise to become advanced heat transfer fluids in terms of thermal performance [1]. While enhancing thermal characteristics, the solid-liquid mixtures present an unavoidable disadvantage in terms of pumping cost for economic operation of thermal-fluid systems. In addition, there is a lack of agreement between experimental data provided in the literature. We can find that this issue of nanofluids resembles that of designing new materials. As Suh showed in Figure 1 (a) on materials development, many nanofluids researchers tend to view the nanofluid field as a highly coupled "tetrahedron" whose four vertices (performance, properties, structure, and processes) are interconnected to each other as shown in Figure 1 (b). [2]



(a) (b)

Figure 1. The traditional tetragonal views of the general materials world and similar nanofluid world

The present design study has a big merit to systemize the nanofluid work and to reduce a lot of trial-error efforts. [2] The present work found that there would be no comprehensible design strategy in developing nanofluids. In this work, the Axiomatic Design (AD) theory is applied to standardize the design of nanofluids in order to bring its practical use forward. According to the Independence Axiom of the AD theory, the excessive couplings between the functional requirements and the parameters of a nanofluid system prevent from meeting the functional goals of the entire system. At a parametric level, the design of a nanofluid system is inherently coupled due to the characteristics of thermal-fluid system; the design parameters physically affect each other sharing sub-level parameters for nanoparticles with making a feedback loop. Even though parts of the nanofluids are naturally coupled, it is possible to reduce and/or eliminate the degree of coupling by help of AD principles. From the perspective of AD, this implies that we are able to ascertain which nanofluid system is better one in the light of functional achievement.

2. Nanofluid Design with Axiomatic Design

Figure 2 shows the design domains of nanofluids in terms of new materials design. At the development of a nanofluid, the customers in industries of thermal-fluid systems ask a better heat removal without significant pumping cost increase. We can start to design a nanofluid according to AD theory.

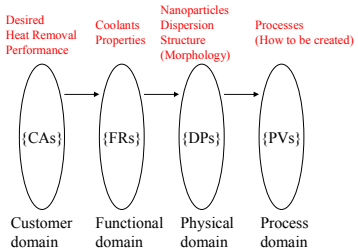


Figure 2. Nanofluid design domains (based on Suh [2])

The top FR and DP can be stated as
FR_0 = Design a new coolant with a better heat removal capability while preventing significant pumping cost increase
DP_0 = Nanofluid (or coolant with nanoparticles)

For a thermal-fluid system adopting convection heat transfer regime, the FRs of nanofluids may be stated as
FR_1 = Provide high thermal performance = Q
FR_2 = Provide low pumping power (penalty) = W
FR_3 = Provide high stability of dispersion = V_t

Thermophysical properties (ρ, μ, c_p and k) of a coolant are important parameters affecting thermal performance and pumping power. Here, density and heat capacity are fully dependent from selections of materials regardless of morphology of nanofluids (dispersion structure of nanoparticles). Therefore, we can select thermal conductivity and viscosity as DPs. In addition, dispersion stability is very essential requirement of nanofluids. The DLVO theory provided the quantitative explanation of agglomeration by equating the total interaction potential equation V_T term as the summation of the dispersion attraction V_A and electrostatic repulsion V_R especially for electrostatic stability. [3]

$$V_T = V_R + V_A \quad (1)$$

To extend into steric stability with polymers, the total interaction can be explained with

$$V_T = V_R + V_A + V_S \quad (2)$$

As the third functional requirement, we propose V_{max}.

$DP_1 = k_{nf}$, $DP_2 = \mu_{nf}$, $DP_3 = V_{max}$

Every step that we decompose a sub-level for detailed design, we should check coupled relations. The Design Matrix of this level FRs may be written as

$$\begin{Bmatrix} Q \\ W \\ V_T \end{Bmatrix} = \begin{bmatrix} X & x & x \\ x & X & x \\ x & x & X \end{bmatrix} \begin{Bmatrix} k_{nf} \\ \mu_{nf} \\ V_{\max} \end{Bmatrix} \text{ or } \begin{Bmatrix} Q \\ W \end{Bmatrix} = \begin{bmatrix} X & x \\ x & X \end{bmatrix} \begin{Bmatrix} k_{nf} \\ \mu_{nf} \end{Bmatrix} \quad (3)$$

The reason why the present nanofluids are in coupled design can be recognized through the sub-level design process. To find proper design parameters, the backing theories are based on features of nanoparticles such as particle size, shape and its number density as key changes in the new coolant [4]. The DP_1 can be decomposed into three specific FRs according to the effective thermal conductivity relation.

FR_{11} = Control primary particle number per unit volume
FR_{12} = Control primary particle shape
FR_{13} = Control primary particle size
DP_{11} = m, DP_{12} = ψ, DP_{13} = d_p

The DP_2 is decomposed into three specific FRs according to the effective viscosity relation.

FR_{21} = Control primary particle number per unit volume
FR_{22} = Control primary particle shape
FR_{23} = Control primary particle size
DP_{21} = m, DP_{22} = ψ, DP_{23} = d_p

Therefore, DP_3 is decomposed into specific FRs.

FR_{31} = Increase electrostatic repulsion (V_R)
FR_{32} = Decrease London van der Waals attraction (V_a)
FR_{33} = Increase steric repulsion (V_s)
DP_{31} = ζ (zeta potential), DP_{32} = a (=d_p/2), DP_{33} = Γ (adsorbed amount of polymer(or surfactant)) or δ (adsorbed layer thickness) Through this process, we found that all DP_X of the first level are coupled with particle size, d_p. (DP_{13} = d_p, DP_{23} = d_p, DP_{32} = a (=d_p/2),) Even, FR_1 and FR_2 share same DPs in the sub-level. Figure 3 shows the overall design matrixes of nanofluid coolant. Figure 4 shows the tree of nanofluid axiomatic design. A feedback junction (F), found when there is a coupled design and indicates that feedback (red-lines) is required and that the Independence Axiom is violated. To realize the original ideas of nanofluid, we should seek some ways to reduce couplings in design parameters. Fortunately, it is known that the particle shape has the stronger effect on viscosity rather than thermal conductivity while the particle diameter has the stronger effect on thermal conductivity. It is also known that the particle shape has the stronger effect on viscosity rather than thermal conductivity while the particle diameter has the stronger effect on thermal conductivity. [5] We can redesign the design matrix. For example,

FR_{12} = Control particle size, DP_{12} = d_p
FR_{22} = Control particle shape, DP_{22} = ψ ($P^{-1/2}$)

Figure 5 shows the promising design matrix and tree of nanofluids.

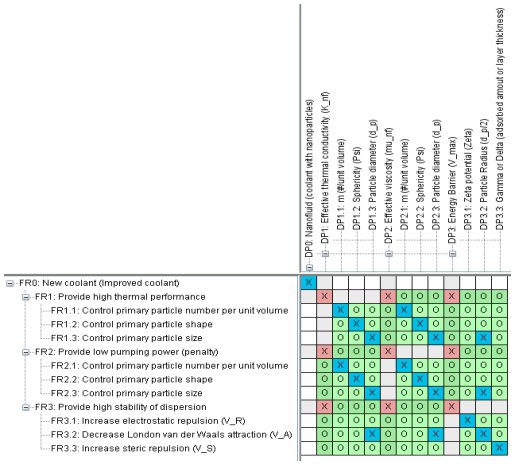


Figure 3. Design matrix of nanofluid

Figure 4. Hierarchical tree of nanofluid design

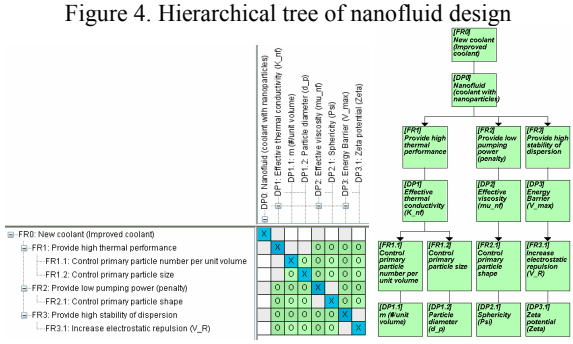


Figure 5. Design matrix and tree candidates

This first design study contributes to establishment of the standard communication protocol of nanofluid.

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