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ScienceDirect
Applied Thermal Engineering 29 (2009) 75–90
APPLIED THERMAL ENGINEERING
www.elsevier.com/locate/apthermeng

An axiomatic design approach in development of nanofluid coolants

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Received 4 September 2007; accepted 4 February 2008
Available online 12 February 2008

Abstract

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. 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. 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 systemize 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 feasible in the light of functional achievement. This study contributes to establishment of the standard communication protocol in the nanofluid research.

Keywords: Nanofluid; Heat transfer; Axiomatic design; Coolant; Nanoparticle

1. Introduction

Nanofluids introduce a unique approach for treating more effective heat removal in thermal-fluid systems. In general, current thermal-fluid systems strive to achieve high thermal performance in an effort to maximize economics and safety. One way to achieve this purpose is by adding nanoparticles to the coolant of the system in order to improve thermal properties of the coolant, itself. It has been shown that a nanofluid consisting of metal or metal oxides nanometer-sized particles dispersed in a pure fluid such as water and ethylene glycol has a higher effective thermal conductivity than that of the pure fluid [1–3]. However, what is lacking for the practical use of nanofluids in a wide range of applications is an agreement or reproducibility between experimental data [4]. As the reason, we can find that this issue of nanofluids resembles similar problems of materials design. As Suh shown in Fig. 1a 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 Fig. 1b [5].

The present design study has shown big merits in systemizing the nanofluid work and reducing a lot of trial-and-error efforts [5]. Furthermore, adding nanoparticles into a base liquid has shown not only an increase of effective thermal conductivity as a thermal characteristic advantage but also an increase of effective viscosity as an important drawback. For example, when the amount of particles is small, the heat transfer increase that is acquired may be small. On the other hand, too many particles may result in large shear stresses and pumping power requirement as a result. It is considered as an issue of competition or optimization [6]. This type of issues have existed even in developments of traditional heat

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doi:10.1016/j.applthermaleng.2008.02.004

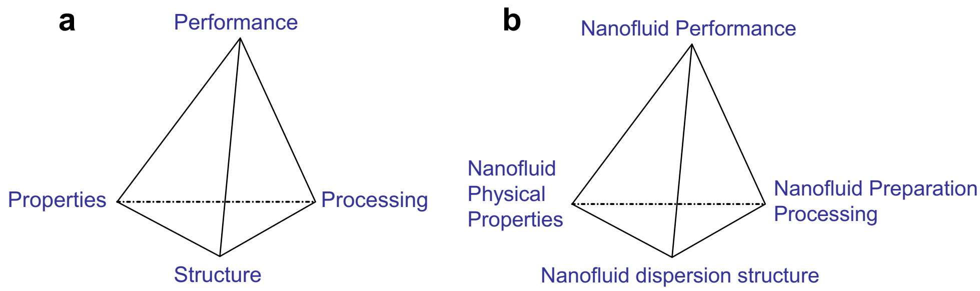

Fig. 1. The traditional tetragonal views of the general materials world and similar NF world [5].

transfer enhancement technologies which have been evaluated for the heat transfer performance under consideration of the competition between heat and flow performances. Therefore, there is the necessity for systematic design approach of nanofluids in order to bring nanofluid's practical use forward. The lack of an agreement between experimental data acquired by different groups can be due to different preparation method, different suspension state, and different size or agglomeration of nanoparticles, as well as different shape of particles. In addition to considering general preparation methods of nanofluids, additional factors should be considered depending on a uniqueness of each application area. For example, nuclear industry should consider coolant activity by neutron radiation. In case of electronics application, a dielectric constant should be considered while the magnetic field effect on particles should be considered for high magnetic field environment of application. We presume that the 'object-oriented design' of the nanofluids should be necessary on the basis of the research achievements previously done. Given the top functional requirements that a nanofluid should meet, the object-oriented design enables us to have insights about not only what the must-have items are but also how we take the items, which is useful when we adopt an innovative concept that we have not dealt with before. The object-oriented design is akin of top–down thinking processes that organize objects and means while minimizing individuals' subjectivity. Here we will illustrate an object-oriented design of nanofluids to give a systematic philosophy of developing such new coolant using Axiomatic Design (AD), which is one of the object-oriented design methodologies. We are therefore able to have the standard communication protocol on designing nanofluids. The design product developed by the present nanofluid theories and design axioms of the AD theory ensures achieving high thermal performance in an effort to maximize economics and safety.

2. Nanofluid coolant

2.1. Brief description of nanofluid as a coolant of a thermal-fluid system

It is necessary to remind the features of nanofluids required as a coolant in a thermal-fluid system. Because of small dimensions of nanoparticles, it has been considered that nanofluids may be easily fluidized and consequently, can behave like a fluid. This means nanofluids are considered as a conventional homogeneous single-phase fluid with assumptions of a uniform distribution of nanoparticles, negligible motion slip, and thermal equilibrium conditions [7]. The general consideration of such fluid in a thermal-fluid system is on forced convection heat transfer of uniformly heated tube under laminar or turbulent flow. A promising coolant of a thermal-fluid system should meet the requirements of both heat removal capability and pumping power limitation. To identify what kind of parameters as a desirable coolant are important, heat transfer backgrounds are reminded.

The heat removal capability can be expressed as

$$\dot{Q} = \dot{m}C_p\Delta T = qA = hA(T_w - T_f) = \pi k Nu L(T_w - T_f) \quad (1)$$

Similarly the pumping power is

$$\dot{W} = \dot{V}\Delta p = \dot{m}\frac{\Delta p}{\rho} = f\frac{8\dot{m}^3 L}{\pi^2\rho^2 D^5} \quad (2)$$

$$Nu = CRe^m Pr^n; \quad f = CRe^{-a} \quad (3)$$

In Nu number, C, m, and n are often independent of the nature of the fluid and dependent of the geometry of a system. The nature of fluid is expressed with different Prandtl numbers.

$$\frac{Nu}{Pr^n} = CRe^m$$
$$Re = \frac{\rho u D}{\mu}, \quad Pr = \frac{c_p\mu}{k} = \frac{\nu}{\alpha}, \quad \alpha = \frac{k}{\rho c_p} \quad (4)$$

Above equations show that convection heat transfer and pumping power for general application depends on coupling of coolant's thermo-physical properties (ρ, μ, c_p and k) if everything else is same [7]. Because nanofluids technology is to change such properties differently from other heat transfer enhancement methods in terms of system geometry, we should consider the nanofluids properties. The effective thermo-physical properties can be considered as follows. Basically, it is noted that the equations for other properties except viscosity are based on simple approximation of linear variation between two components depending on fraction.

$$\text{Density}: \rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_{np} \quad (5)$$

$$\text{Specific heat}: (\rho c_p)_{nf} = (1-\phi)(\rho c_p)_{bf} + \phi(\rho c_p)_{np} \quad (6)$$