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Thermal-fluid Characterizations toward a Standardized Design of Nanofluids Experiments

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1. Introduction

Nanofluids [1] or nanoparticles-fluid mixtures including metal or metal-oxide nanoparticles have shown the improved thermal performances compared to water. However, a design of a nanofluid system is inherently coupled not only nanofluid compositions such as nanoparticles, base-fluids and, dispersants but also thermal-fluid parameters such as heat transfer and pumping power due to the characteristics of a thermal-fluid system. Furthermore, the changes of boiling heat transfer and CHF in nanofluids are known to mainly depend on liquid-surface combination factors expressible as surface wettability (contact angle) due to fouling, deposition or coating by nanoparticles in a form of agglomerates or promiscuous porous layers including additional considerations of hot spot dissipation and delaying burnout depending on a liquid type and surface [2,3]. The phenomenon can add a crud-like issue as an additional nanofluids' coupling factor when nanofluids put into the primary parts of NPPs. Crud deposition has been one of important challenges known as crud induced power shift (CIPS) on fuel rod or axial offset anomaly (AOA) and radioactive contamination in cooling-water systems and spent-fuel storage areas [4]. Therefore, the R&D of nanofluids for nuclear systems should consider the complex couplings in essence. The ultimate goal of the nanofluids R&D to ANPP is developing a nanofluid formulation to tailor the desired properties by removing the various couplings of a nanofluid nuclear safety system as much as possible, and proper nuclear system components to help the decouplings. This should realize us to do some approaches better even from nanofluids preparation, nanofluids performance tests to a decoupled design of nanofluid engineered system. Here we report thermal-fluid characterization of nanofluids toward a standardized design of nanofluids experiments for advanced nuclear power plants following the Axiomatic Design approach for standard nanofluids, our previous study.

2. Methods and Results

As the first step, the present work selected the materials of nanofluids such as ZnO and SiC in terms of the possibility of nanoparticles contributing to not only improvement of thermal-fluid performance, but also, improvement of reduction of coolant activity and corrosion. Thermal-fluid characterizations were carried out under the control of the preparation methods.

2.1 Experimental Methods

Thermal-fluid characterizations of ZnO and SiC nanoparticles-mixtures were carried out through measurements of physical properties such as thermal conductivity, viscosity, pH, conductance, and surface tension. Thermal conductivity is measured by a transient heated needle method. The probe with 60 mm length and 1.3 mm diameter are immersed vertically into liquids. It is noteworthy that instability and nonequilibrium of liquid and easily make a big jump of thermal conductivity as errors. Therefore, all measurements were carried out carefully ensuring that there is no shaking, mixing, or vibration of the fluid during or before the measurement. A ring-type surface tension analyzer was used for surface tension. Viscometer with water jacket to keep temperature at a fixed condition was used to get the viscosities according to the temperatures. A pH/conductivity meter displayed the changes of pH and conductance of solutions. In addition, the nanoparticles deposition effects responsible for boiling and CHF are investigated by using a sessile drop contact angle analyzer.

2.2 Validation Tests and Effects of Stabilizer on Physical Properties

Researchers have used various stabilizers such as surfactants, acids and bases to prepare nanofluids because nanoparticles-liquid mixtures showed the unstable dispersions substantially resulting in the unreliable measurements. Therefore, the effects of stabilizer on the properties of fluids were investigated as listed in Table I. HCl and NaOH have been widely used for controlling the surface charge of nanoparticles to increase the repulsion force in order to make stable dispersion. It is shown that there are the minimal changes of thermal–fluid properties. The surfactant, SDS is most widely used as dispersants in colloidal applications. Even though SDS has a nominal effect to pH, k, and σ, it reduces surface tension up to 33 % in a concentration close to CMC. It is well-known that the addition of SDS causes additional effects for boiling bubbles parameters and surface wettability. It should be noted that the surfactants may tend to break down with increasing temperature causing failure of stable dispersion. The viscosities of pure water are known to be 1.081 (17 ^{o}C), 1.054 (18 ^{o}C), 1.028 (19 ^{o}C) and 1.003 (20 ^{o}C) in the literature. For thermal conductivity data of pure water acquired as validation tests of thermal conductivity measurement, the average values in each temperature are 0.5971 (18.96 ^{o}C) W/mK and 0.6293 (29.45 ^{o}C) W/mK. In the literature, thermal conductivities are 0.5979 W/mK and 0.6142 W/mK, respectively, representing -1% and 2.5% errors. Therefore, the uncertainty of thermal conductivity may be considered to be nominal. Mainly, the shaking of fluids and instability of nanofluid dispersion state showed unreasonable errors or big jumps from a reference value.

Table I: Measurements of Physical Properties of Fluids

Solutions	pH	S (μS)	k W/mK	μ mPa·s	σ mN/m
HCl 0.1 M	1.1	93100	0.614	0.99	69.77
NaOH 0.1 M	13.31	46700-23000	0.609	1.04	69.18
PW	6.84	3.06-13.16	0.614	1.03	69.42
PW+0.1 M HCl (10 %)	1.89	4760	0.614	0.98	69.7
PW+0.1 M NaOH (10%)	12.3	2090	0.602	1.02	69.14
ZnO 0.001 v%+HCl (10%)	5.57	1239	0.609	0.97	65.61
PW-0.001 M SDS	6.05	-	0.602	1.01	46.45

2.3 Thermal Conductivity and Viscosity

Thermal conductivities and viscosities were investigated for the prepared ZnO and SiC nanoparticles-water mixtures. However, ZnO nanoparticles showed the settle-down phenomena due to strong agglomerations even in case of pH control far from isoelectric point and SDS addition. Its thermal conductivity measurement could not be acquired rightly. We deal more with the phenomena based on the viscosity data for the ZnO nanoparticles-water mixtures. On the other hand, SiC nanofluid could be prepared well enough through the surface charging with pH control. Thermal conductivities of 0.01 v% and 1 v% SiC-water nanofluids were acquired. In average, 0.5966 W/mK and 0.6214 W/mK are acquired for 19.01 ^{o}C and 18.49 ^{o}C, respectively. The corresponding water values are 0.5980 W/mK and 0.5971 W/mK. 1 v% SiC nanofluid (~11.8 pH, 1827 μS) made 4.1 % thermal conductivity enhancement while 0.01 v% SiC nanofluid (~11.59 pH, 1746 μS) showed no substantial change.

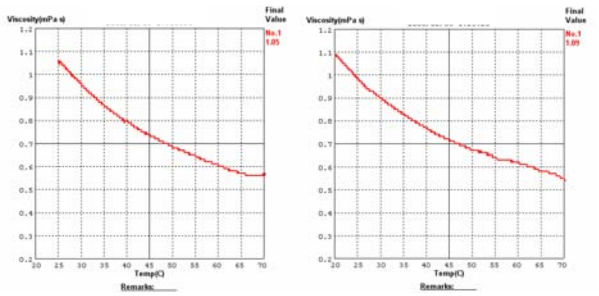

Fig. 1. Viscosity-temperature curves of 0.01 v % ZnO and SiC nanoparticles-water mixtures, respectively.

2.4 Sessile drop test of nanofluids

Various colloidal applications and surface modification techniques have been developed and under development in industries. The sessile drop technique is the most widely used one to develop liquid-surface modification techniques in coating, cleaning and manufacturing. So far, the deposition phenomena of nanofluids might be classified into two reasons of boiling-induced coating in low concentration and initial dip-coating in higher concentration. If we design a nuclear safety system using the mechanisms, the design optimal parameters can be acquired from characterization of nanofluids-surface interaction. Also, the crud-deposition effects might be investigated through the characterization. To investigate the deposition effect of ZnO and SiC materials on the evaporated surface of nanofluids, the other sessile drop test was carried out. The result can be considered together in solving both crud-issue and crud-like issue of nanofluid. The nanoparticles-deposited copper samples were prepared through evaporation of water under ~150 ^{o}C heating condition after dropping 3 ml nanofluids onto the sample. The pure water droplets showed the initial contact angle reductions and spreading phenomena with time resulting in complete wetting after about 5 minutes.

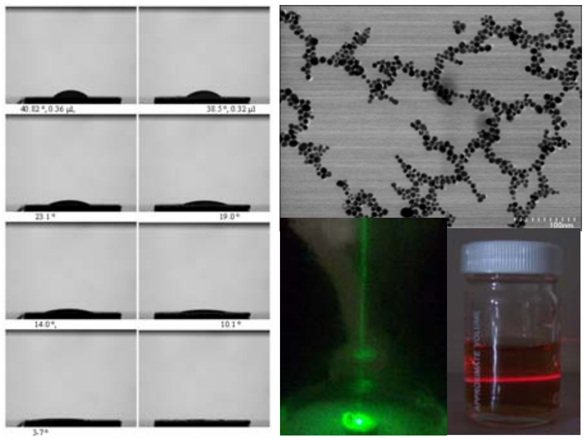

Fig. 2. Spreading phenomena of 0.01 v% SiC and 0.01 v% ZnO nanoparticles-deposited surfaces; Pulsed-Laser-Ablation-in-Liquids nanofluids fabrication R&D

With this study for proper Design of Experiments, we are developing a variety of materials-based nanofluids using the PLAL as a promising nanofluid preparation method for the present on-going nanofluid R&D for ANPPs with the NF AD protocol for the Nuclear Nanofluid Engineered Safety Systems.

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