# Measurement and Estimation of Effective Thermal Conductivity for Sodium based Nanofluid using 3-Omega Method

Sun-Ryung Oh[a], Hyun Sun Park[a*], Moo Hwan Kim[b]
[a]*Division of Advanced Nuclear Engineering*
*Pohang University of Science and Technology (POSTECH)*
*77 Cheong-am-ro, Nam-gu, Pohang, Gyeongbuk, 37673, Republic of Korea*
[b]*Korea Institute of Nuclear Safety*
*62 Gwahak-ro, Yuseong-gu, Daejeon, 34142, Republic of Korea*
[*]*Corresponding author: hejsunny@postech.ac.kr*

## 1. Introduction

The sodium-cooled fast reactor (SFR) is one of generation IV type reactors and has been extensively researched since 1950s. A strong advantage of the SFR is its liquid sodium coolant which is well-known for its superior thermal properties. However, in terms of possible pipe leakage or rupture, a liquid sodium coolant possesses a critical issue due to its high chemical reactivity which leads to fire or explosion. Due to its safety concerns, dispersion of nanoparticles in liquid sodium has been proposed to reduce the chemical reactivity of sodium. In case of sodium based titanium nanofluid (NaTiNF), the chemical reactivity suppression effect when interacting with water has been proved both experimentally and theoretically [1,2].

Suppression of chemical reactivity is critical without much loss of high heat transfer characteristic of sodium. However, the effect of nanoparticles on thermal properties of liquid sodium has not been extensively studied yet. As effective thermal conductivity is dominant for evaluating heat transfer performance, 3-omega method is adapted as it can be easily manufactured and applied which is appropriate for lab-scaled sodium study. As there is no research conducted for applying 3-omega sensor in liquid metal as well as high temperature liquid, the sensor development is performed for using in NaTiNF as well as effective thermal conductivity model validation.

Based on the acquired effective thermal conductivity of NaTiNF, existing effective thermal conductivity models are evaluated. There is no existing thermal conductivity model which uses liquid metal as a base fluid. Also, there is no existence of reliable theory to predict the anomalous thermal conductivity of nanofluids. Therefore, through comparison of various effective thermal conductivity models, most well-predicting model is selected for nanofluid which uses sodium as a base fluid.

## 2. Experiment

For the 3-omega sensor calibration, as reference media, ethylene glycol and bare sodium are used. The calibrations are performed for ethylene glycol and bare sodium at temperature 40 to 150 ℃ and 120 to 180 ℃, respectively. After the calibration, the 3-omega sensor is applied to measure a thermal conductivity of NaTiNF with 0.2vol.% of titanium nanoparticles. Thermal conductivities are measured at 120, 150, and 180 ℃ along with repeatability test of 6 times at each target temperature. Micro-electro-mechanical systems (MEMS) technique is used for the sensor fabrication.

### *2.1. 3-omega sensor*

The 3-omega sensor is fabricated using micro-electro-mechanical systems (MEMS) technique. First, gold of 300nm gets deposited onto borosilicate glass wafer of 500nm with titanium of 10nm as an adhesion layer. From a standard photolithography technique, the sensor is patterned on the gold. The sensor is composed of fine sensing/heating line: width of 20μm and length of 1mm. Kapton taping of 5mm width is done on the gold part where input and output of both voltage and current occur. Since the deposition of dielectric layer on the sensor enabled a measurement of electrically conducting liquid [3], silicon nitride of 500nm is deposited on top as a dielectric layer using low temperature PECVD. After the removal of the tape, soldering is performed. Resistance of the 3-ω sensor is measured by Agilent 34401A multimeter by 4 wire method.

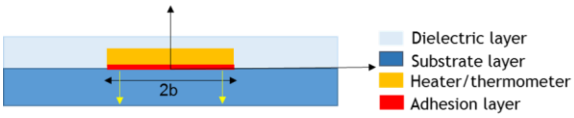


Figure 1. Composition of the 3-omega sensor

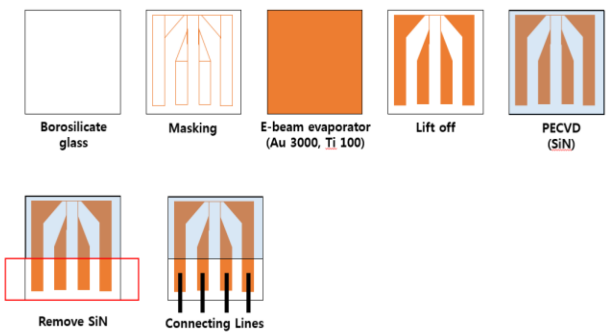


Figure 2. MEMS fabrication of the 3-omega sensor

### *2.2. Experimental setup*

All experiments are safely conducted inside the glove box with Ar gas quality of 99.9999% to prevent oxidation of liquid sodium. Titanium nanoparticles of 0.2 volume fraction is added into the melted sodium, then mixed through physical stirring while being heated in a heating mantle. As a digital overhead stirrer, IKA Eurostar 60 is used with R 1303 dissolver stirring blade. To ensure a homogeneous dispersion of nanoparticles, the nanofluid is mixed at 800rpm for minimum 2 hours. Once the preparation of nanofluid is completed, the breaker containing the NaTiNF gets transferred for a cool down. Once the NaTiNF gets cooled, a strip heater is wrapped around the beaker to apply heat at specific target temperature.

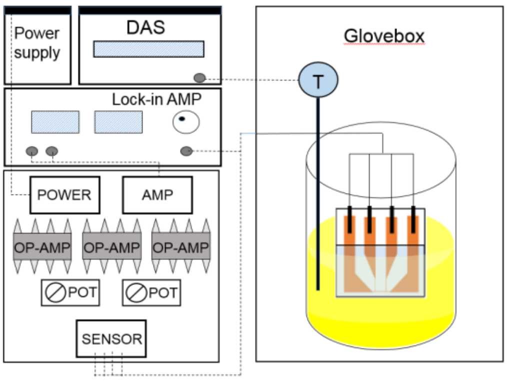


Figure 3. Experimental setup of liquid sodium thermal conductivity measurement

The sensor gets connected with a lock-in amplifier (SR810 DSP) and the circuit which contains potentiometers, then the power is applied to the circuit. The sensor is carefully emerged into the liquid sodium to avoid any contact of liquid sodium with soldered lines. Through LabView program, thermal conductivities are recorded at each measurement with frequency range from 1.5 to 3000Hz.

### 3. Result & discussion

In this study, the effect of titanium nanoparticles on liquid sodium thermal conductivity is investigated experimentally. Pure titanium nanoparticles are purchased from Sigma-Aldrich and the diameter of particles is smaller than 100nm. Both the thermal conductivities of liquid sodium and sodium-titanium nanofluid (NaTiNF) are acquired using 3-ω sensor. For the reference value of liquid sodium, the polynomial established by Argonne National Laboratory is used.

$$k = 124.67 - 0.11381T + 5.5226\times10^{-5}T^2 - 1.1842\times10^{-8}T^3 \qquad (1)$$

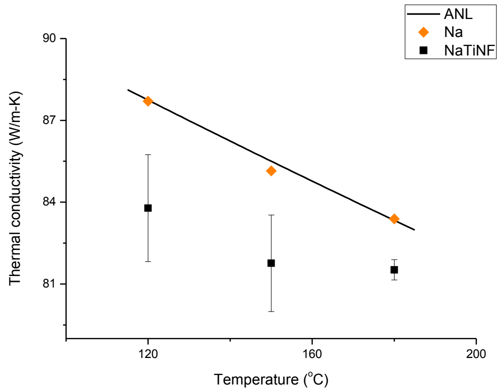


Figure 4. Comparison of thermal conductivities of liquid sodium for reference, experimentally acquired sodium and sodium-titanium nanofluid

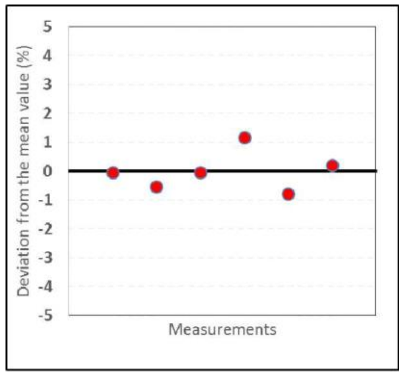


Figure 5. Deviation of the experiment data for liquid sodium at T = 180℃

As shown in figure 4, the experimentally acquired values for liquid sodium exhibit good agreement with the calculated reference values. In order to obtain the precise measurements, at each target temperature, all measurements are repeated 6 times. Once the sensor is calibrated, thermal conductivity measurement of NaTiNF is performed with the same method. The uncertainty analysis for the sensor is performed, and based on the calculation the uncertainty is below 1%.

$$k = -\frac{P}{2l\pi}\left(\frac{\ln\omega_1 - \ln\omega_2}{\Delta T_1 - \Delta T_2}\right) \qquad (2)$$

$$U_k = -\left[\left(\frac{\partial k}{\partial P}U_P\right)^2 + \left(\frac{\partial k}{\partial \omega_1}U_{\omega_1}\right)^2 + \left(\frac{\partial k}{\partial \omega_2}U_{\omega_2}\right)^2 + \left(\frac{\partial k}{\partial T_1}U_{T_1}\right)^2 + \left(\frac{\partial k}{\partial T_2}U_{T_2}\right)^2\right] \qquad (3)$$

Thermal conductivity of liquid sodium is known to have degrading trend as temperature increases. The NaTiNF follows the degrading trend of liquid sodium except it exhibits greater drop of thermal conductivity at each corresponding temperature. Interestingly, the thermal conductivities of NaTiNF at 120 and 150 ℃ show similar reduction while the impact of titanium nanoparticles seem to be greatly reduced at 180 ℃. From this experiment, titanium nanoparticles prove to have a significant influence on thermal conductivity of liquid sodium, but its impact is expected to be greatly reduced as temperature increases.

There are various nanofluid models that predict the impact of nanoparticles on thermal conductivity of base fluid. So far, all existing nanofluid models are developed to predict the heat transfer enhancement of effective fluid. Typically, in effective thermal conductivity equation, a base fluid has lower thermal conductivity than a nanoparticle. However, titanium nanoparticle has a thermal conductivity of 21.9 W/m-K which means thermal conductivity of base fluid, a liquid sodium of 89.4 W/m-K, has significantly higher thermal conductivity than the nanoparticle. Also, there is no available nanofluid model for the case of liquid metal and metal nanoparticle. In an attempt to find a model that best predict the effective thermal conductivity of NaTiNF, various nanofluid models are plotted.

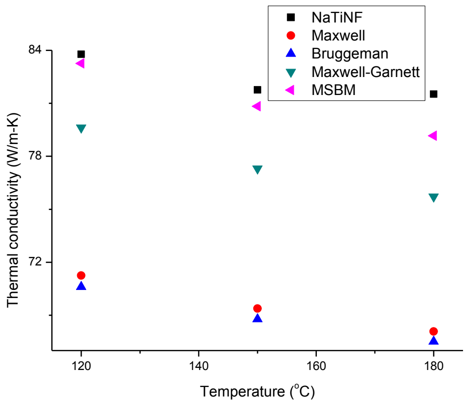


Figure 6. Comparison of various effective thermal conductivity models for NaTiNF

The classical Maxwell equation factored in only the thermal conductivities of a particle and a base fluid, and a volume fraction of the particle. Maxwell model predicts the effective thermal conductivity of nanofluid under the assumption of a homogeneous suspension of spherical nanoparticles. Also, this model has two critical assumptions: no interactions between particles and negligible interfacial resistance between a liquid and a particle. As the liquid sodium and metal nanoparticles have a strong chemical bond, the applied assumptions in the Maxwell model cannot adequately explain or predict the thermal property. Most nanofluid models are based on the Maxwell equation which encountered only the conduction term. Therefore, models which include other factors such as Brownian motion or interfacial resistance should be considered.

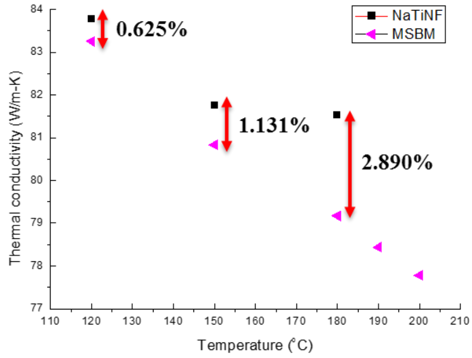


Figure 7. Effective thermal conductivity comparison between NaTiNF and MSBM model

The Multisphere Brownian model (MSBM) comes close predicting the effective thermal conductivity of NaTiNF. Both Maxwell-Garnett (MG) and MSBM consider the impact of Brownian motion. However, the main difference between the MSBM model and other established models used is the consideration of interfacial thermal resistance, also known as thermal boundary resistance.

$$k_{eff} = k_f \left(1 + A\mathrm{Re}^m \mathrm{Pr}^{0.333} \phi\right)\left(\frac{\left[k_p(1+2\alpha)+2k_m\right]+2\phi\left[k_p(1-\alpha)+k_m\right]}{\left[k_p(1+2\alpha)+2k_m\right]-\phi\left[k_p(1-\alpha)+k_m\right]}\right) \quad (4)$$

In this paper, as the interfacial thermal resistance of liquid sodium is unknown, the available value of water is used instead [4]. The interfacial resistance can be a crucial term for predicting effective thermal conductivity of liquid metal base fluid and metallic nanoparticles. Therefore, either through experiment or simulation, finding the interfacial resistance of liquid metal is needed to establish the effective thermal conductivity model for sodium based nanofluid.

## 4. Conclusions

Thermal conductivity measurement is performed for liquid sodium based titanium nanofluid (NaTiNF) through 3-Omega method. The experiment is conducted at three temperature points of 120, 150, and 180 ˚C for both pure liquid sodium and NaTiNF. By using 3-omega sensor, thermal conductivity measurement of liquid metal can be more conveniently conducted in lab-scale. Also, its possibility to measure the thermal conductivity of high temperature liquid metal with metallic nanoparticles being dispersed is shown. Unlike other water or oil-based nanofluids, NaTiNF exhibits reduction of thermal conductivity compare with liquid sodium. Various nanofluid models are plotted, and it is concluded that the MSBM which considers interfacial resistance and Brownian motion can be used in predicting the effective thermal conductivity of NaTiNF. By correctly find the interfacial resistance of liquid sodium either through experiment or simulation, it is expected that the effective thermal conductivity model for liquid metal based nanofluid can be established.

## REFERENCES

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