2018

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Experimental Study on Physical Properties of CuO - PVE Nano-oil and its Mixture with Refrigerant

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ABSTRACT

A nano-oil is a suspension of nano-order particles in refrigeration oil. Recently, the application of nano-oil as the lubrication oil for refrigerant compressors is proposed to improve refrigeration cycle efficiency. In this study, physical properties of nano-oil such as thermal conductivity, viscosity and dielectric constant were measured experimentally. In addition, those of nano-oil / refrigerant mixture were also measured under pressurized condition. Nano-oil was prepared by dispersing oxidized copper (CuO) nanoparticles into refrigeration oil (Polyvinyl ether; PVE) with the volume fraction of 0.5, 1.0 and 3.0 vol%. Measurement of physical properties of nano-oil was performed under the temperature ranging from 30 to 100 °C. The result shows that thermal conductivity, viscosity and dielectric constant of the nano-oil are larger than those of the base oil. The increment of these properties becomes large with volume fraction of nano-particles. On the other hand, measurement of physical properties of PVE-CuO nano-oil / R410A mixture was performed under the 30 °C of temperature and up to 1.3 MPa of pressure. As a result, thermal conductivity, viscosity and dielectric constant of nano-oil / refrigerant mixture increases compared with those without mixing nano particles for low refrigerant concentration, but the effect of adding nanoparticles with pure oil becomes weak with increasing refrigerant concentration.

1. INTRODUCTION

Innovative technologies for improvement of energy consumption of refrigeration cycles are strongly required for energy saving and resolution of global warming in the last decade. A refrigerant compressor is the component which consumes large energy in refrigeration cycle. The energy consumption of refrigerant compressor is estimated to reach into 80 % of total energy in refrigeration cycle (Jia *et al.*, 2014). Therefore, it is very important to reduce the energy consumption of the refrigerant compressor. Regarding the energy consumption in the refrigerant compressor, there are many kinds of loss such as frictional loss, motor loss, leakage loss, discharge loss and so on. Particularly, large energy is expended by the frictional loss in the refrigerant compressor.

Refrigeration oil is generally used in refrigerant compressor for lubrication. Recently, a nano-oil, which is a suspension of nano-order-size particles and base lubrication oil, is proposed to pursue further improvement of energy consumption of the refrigerant compressor. Many researchers investigated the effect of nano-oil on refrigeration cycle and reported the improvement of the refrigeration efficiency (Jia *et al.*, 2014; Xing *et al.*, 2014) By using nano-oil as lubrication oil in refrigerant compressor, the following advantages can be expected; (a) improvement of thermophysical property of lubrication oil, (b) tribological effect at sliding part, and (c) sealing effect of leakage of refrigerant and so on. In fact, several researchers investigated the effect of adding nanoparticles

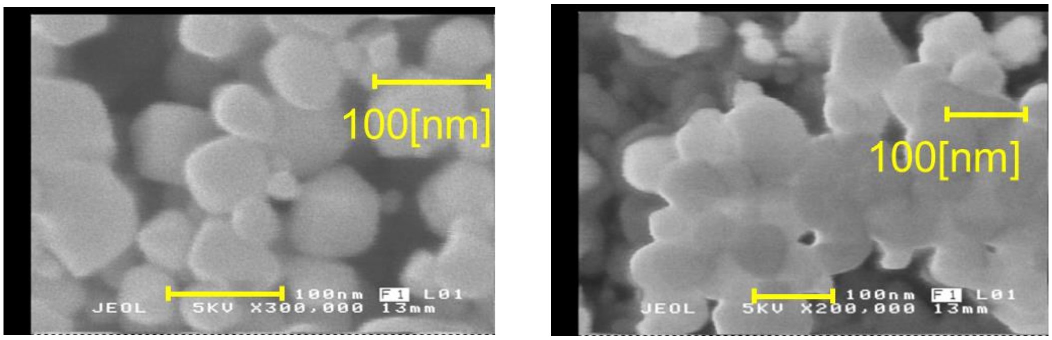

Figure 1: SEM images of CuO nanoparticles taken by ourselves.

to a lubricating oil on the tribological effect and reported the reduction of friction (Lee *et al.*, 2009; Wu *et al.*, 2007; Hu *et al.*, 2002).

Regarding the improvement of thermophysical property, a nanofluid which is the fluid contains nano-order-size particles in a liquid carrier is proposed to improve thermophysical property and heat transfer. There are large amount of studies of thermophysical properties and heat transfer characteristics of nanofluid in the thermal engineering field with achievement of the application to innovative cooling system for CPU, fuel cell and so on (Vanaki *et al.*, 2016; Das *et al.*, 2008). Also, several studies on the thermophysical properties of the nano-oil for lubricant in the refrigerant compressor have been carried out in the refrigeration field and reported the enhancement of thermal conductivity by adding nanoparticles with refrigerant oil (Sanukrishna *et al.*, 2018; Nabil *et al.*, 2017; Pal *et al.*, 2014).

For actual application of nano-oil to refrigeration system, more detailed information of the physical properties of nano-oil except the thermal conductivity is required, and it is also important to investigate not only the effect of addition of nano-particles on the physical properties of refrigeration oil, but also its mixture with refrigerant. However, there are few studies on the physical properties nano-oil / refrigerant mixture. In this study, we measured not only thermal conductivity, but also other physical properties such as viscosity and dielectric constant of nano-oil itself. In addition to the physical properties of nano-oil, such physical properties of refrigerant / nano-oil mixture were also measured and the effect of nano-particles was discussed.

2. EXPERIMENT

2.1 Preparation of Nano-oil

The test nano-oil was prepared by dispersing oxidized copper (CuO) nanoparticles into refrigeration oil. We chose Polyvinyl ether (PVE) as a refrigeration oil in this study. The viscosity grade of PVE was VG 68. The nominal diameter of CuO nanoparticles is 48 nm. Figure 1 shows the SEM images of CuO nanoparticles taken by ourselves. This pictures indicate that the shape of CuO nanoparticles are spherical shape and the particle diameter is less than 100 nm. However, these particles aggregate by the van der Waals force. To get stable nano-oil as much as possible, nano-oil was prepared by the following procedure; i) The CuO nanoparticles were dispersed directly into PVE oil with adding the Sorbitan monolaurate as a dispersant with 5 wt%, ii) ultrasonication was applied to dispersion for 1 hour. In this study, the volume fraction of PVE - CuO nano-oil are 0.5, 1.0 and 3.0 vol%.

2.2 Measurement of Physical Properties of Nano-oil

Figure 2 shows the schematic diagram of a pressure vessel for measurement of physical properties of nano-oil. A sight glass is attached to the side of the pressure vessel. The sensors for measurements of thermal conductivity, viscosity and dielectric constant are installed in the pressure vessel. Therefore, thermal conductivity, viscosity and dielectric constant of nano-oil / refrigerant mixture can be measured simultaneously under pressurized condition. Note that the measurements of physical properties of nano-oil itself without mixing refrigerant was performed under atmospheric pressure. Thermal conductivity, viscosity and dielectric constant are measured by a needle sensor, a

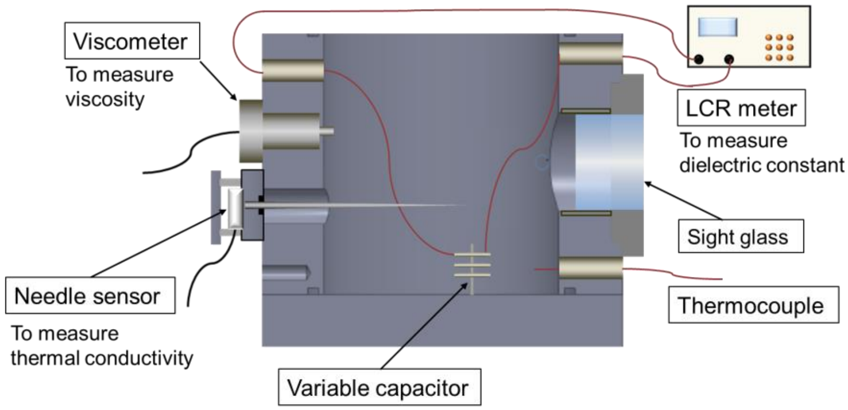

Figure 2: Pressure vessel for measurement of thermal conductivity, viscosity and dielectric constant of nano-oil.

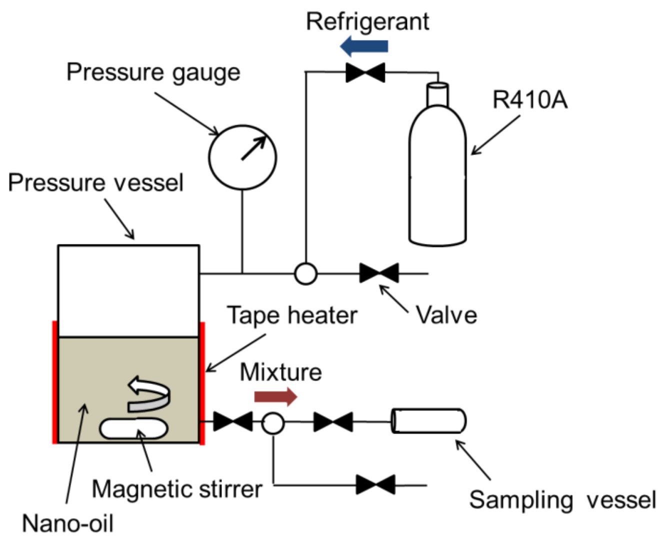

Figure 3: Experimental apparatus for measurement of physical properties of PVE-CuO nano-oil / R410A mixture.

piston type sensor, and a variable capacitor and LCR meter, respectively. The temperature of the test fluid is controlled by a tape heater wrapped around this pressure vessel. The temperature of the test nano-oil ranged from 30 to 100 °C. The test nano-oil was stirred by a magnetic stirrer to prevent from the sedimentation of the nanoparticles.

2.3 Measurement of Physical Properties of Nano-oil / Refrigerant Mixture

Figure 3 shows the schematic diagram of the experimental apparatus for measurement of the physical properties of nano-oil / refrigerant mixture. The apparatus consists of the pressure vessel as explained above, refrigerant cylinder, and sampling vessel. R410A which has good solubility with PVE was used as a refrigerant. R410A was provided to the pressure vessel from the refrigerant cylinder, and nano-oil / refrigerant mixture, i.e. PVE - CuO nano-oil / R410A mixture, was prepared in the pressure vessel before measurement. The temperature of the mixture was stabled at 30 °C by the tape heater wrapped around this pressure vessel. The pressure of the vessel was varied up to 1.3 MPa. The refrigerant concentration of the mixture was measured by a sampling method using the sampling vessel.

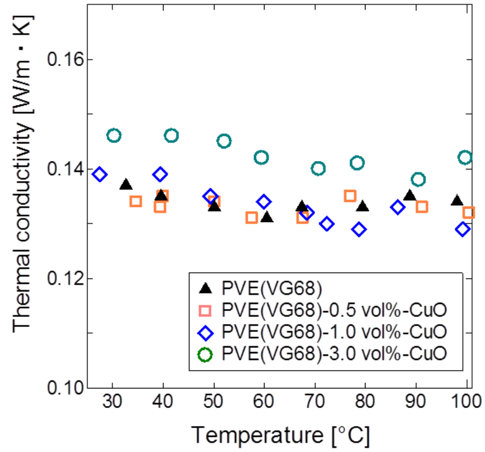

Figure 4: Temperature dependence of thermal conductivity of PVE-CuO nano-oil.

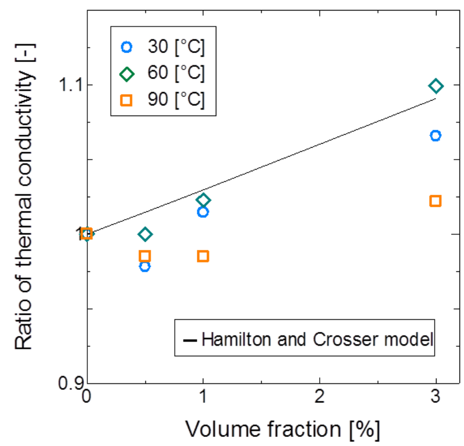

Figure 5: Increasing ratio of thermal conductivity of PVE-CuO nano-oil.

3. RESULTS AND DISCUSSIONS

3.1 Physical Properties of PVE - CuO Nano-oil

3.1.1 Thermal conductivity

Figure 4 shows temperature dependence of thermal conductivity of PVE-CuO nano-oil with the different volume concentration of nanoparticles. Thermal conductivity of nano-oil slightly decreases with the temperature and increases with the volume concentration of nanoparticles. Similar result of the change in the thermal conductivity by adding nanoparticles into refrigeration oil was obtained by other researchers (Sanukrishna *et al.*, 2018).

Figure 5 shows the increasing ratio of the thermal conductivity of nano-oil compared with the pure refrigeration oil. The solid line in this figure represents a thermal conductivity model for suspensions proposed by Hamilton and Crosser (1962) and is given by

$$k_{nf} = \frac{k_p + (n-1)k_{bf} - (n-1)\varphi(k_{bf} - k_p)}{k_p + (n-1)k_{bf} + \varphi(k_{bf} - k_p)} k_{bf} \quad (1)$$

where, k_p, k_{bf}, φ, n are thermal conductivity of particles, thermal conductivity of base fluid, volume fraction of particles and the coefficient of particle shape, respectively. In this study, n is given 3 by assuming that nanoparticles are spherical shape. Although it is very difficult to adjust the temperature of nano-oil at a constant as shown in Fig. 4,

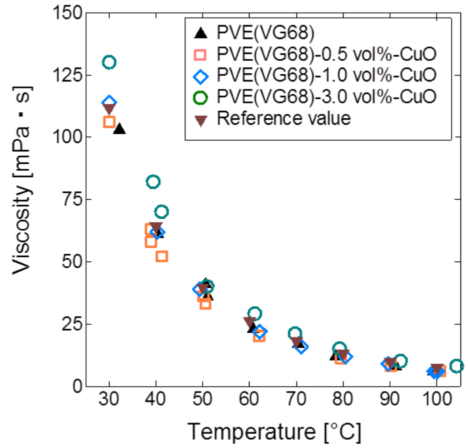

Figure 6: Temperature dependence of viscosity of PVE-CuO nano-oil.

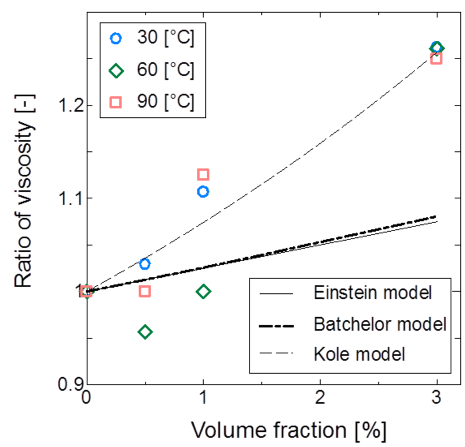

Figure 7: Increasing ratio of viscosity of PVE-CuO nano-oil.

we evaluated the increasing ratio by using measured thermal conductivity. Therefore, the deviation of the increasing ratio are considerably large, but we can observe the change in the increasing ratio of thermal conductivity qualitatively. Figure 5 indicates that about 10 % of maximum increasing ratio of the thermal conductivity is obtained for 3.0 vol % nano-oil because the thermal conductivity of CuO is much higher than the pure oil. The tendency of the variation of thermal conductivity of PVE-CuO nano-oil has similar to the Hamilton and Crosser model, but the increasing level of thermal conductivity is slightly smaller than that calculated by the Hamilton and Crosser model.

3.1.2 Viscosity

Figure 6 shows the temperature dependence of viscosity of PVE-CuO nano-oil. The reference value of PVE in this figure was obtained from the manufacturer. The measured viscosity of PVE is almost consistent to the reference value. The viscosities of pure oil and nano-oil drastically decreases with temperature, but the tendency of decrease of viscosity has similar between pure oil and nano-oil.

Figure 7 shows the increasing ratio of the viscosity of nano-oil compared with the pure refrigeration oil. The solid line and broken lines in this figure are the viscosity model obtained by Einstein (1956), Batchelor (1977), Kole *et al.* (2011). These are expressed by the following equations.

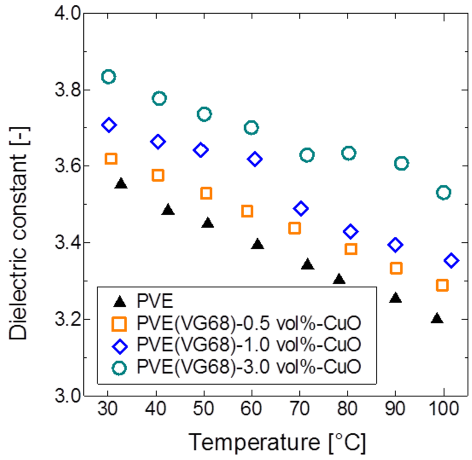

Figure 8: Temperature dependence of dielectric constant of PVE-CuO nano-oil.

Einstein equation

$$\frac{\eta_{nf}}{\eta_{bf}} = 1 + 2.5\varphi \quad (2)$$

Batchelor equation

$$\frac{\eta_{nf}}{\eta_{bf}} = 1 + 2.5\varphi + 6.2\varphi^2 \quad (3)$$

Kole equation

$$\frac{\eta_{nf}}{\eta_{bf}} = \left\{1 - \frac{\varphi}{0.5}\left(\frac{a_a}{a}\right)^{1.3}\right\}^{-1.25} \quad (4)$$

where, η_{nf}, η_{bf} and φ are viscosity of nanofluid, viscosity of base fluid and volume concentration of particles. a and a_a in the Equation (4) are radius of nanoparticles and effective radii of aggregation of nanoparticles, respectively.

As shown in Fig. 7, viscosity of nano-oil increases with increasing volume fraction of nanoparticles, but the increasing ratio does not agree with the Einstein equation and the Batchelor equation. The increasing ratio obtained from our experiment is larger than those calculated by the Einstein equation and the Batchelor equation. The Einstein equation can be applied for the volume fraction of particles less than 1%, and the Batchelor equation extended the Einstein equation for larger volume fraction of particles. Kole *et al.* (2011) pointed out that the calculated viscosity by the Einstein equation and the Batchelor equation does not have agreement with the viscosity of nanofluids. It seems that viscosity increases larger comparing with these equations due to the interaction of the nanoparticles because the particle diameter of nanofluid is too small to apply these equations. In contrast, Equation (4) is obtained by experiments and Kole *et al.* considered the aggregation of nanoparticles in nanofluid. Our results has also similar configuration to the Kole equation.

3.1.3 Dielectric constant

Figure 8 shows the temperature dependence of dielectric constant of PVE-CuO nano-oil. The dielectric constants of both pure refrigeration oil and nano-oil decrease with increasing temperature, and the slope of the configuration is almost the same. In addition, the dielectric constant of nano-oil is higher than that of pure oil, and it becomes large with increasing the volume fraction of nanoparticle, since the dielectric constant of nanoparticles is higher than that of pure oil. These increasing tendency is similar to other properties such as thermal conductivity and viscosity. The dielectric constant of 3.0 vol% nano-oil increases about 10 % comparing with the pure oil.

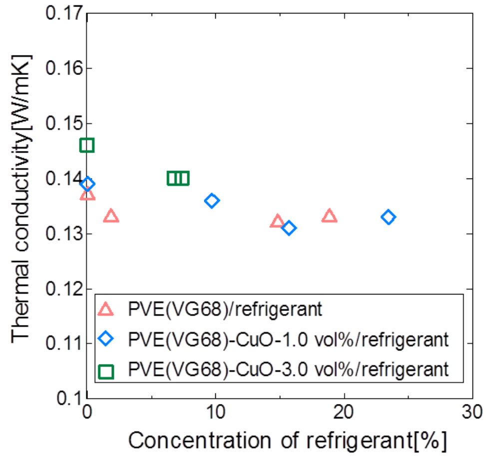

Figure 9: Thermal diffusivity of PVE-CuO nano-oil / R410A mixture as a function of refrigerant concentration.

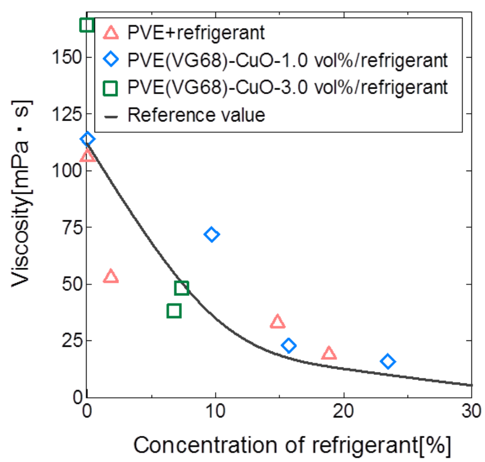

Figure 10: Vixcosity of PVE-CuO nano-oil / R410A mixture as a function of refrigerant concentration.

3.2 Physical Properties of PVE-CuO nano-oil / R410A Mixture

Figures 9, 10 and 11 show the thermal conductivity, viscosity and dielectric constant of the PVE-CuO nano-oil / R410A mixture as a function of the refrigerant concentration of the mixture, respectively. Although these results have large scattering because of the difficulty of measurements, these figures qualitatively indicate that thermal conductivity, viscosity and dielectric constant of nano-oil / refrigerant mixture increase compared with those without mixing nanoparticles for low refrigerant concentration. The effect of adding nanoparticles with pure oil appears to be weaken with increasing refrigerant concentration. Especially, regarding the dielectric constant, it does not largely increase for nano-oil / refrigerant mixture although it obviously increases by adding nanoparticles for nano-oil itself as shown in Fig. 8.

Considering the actual condition in refrigerant compressor, the refrigerant concentration in refrigeration oil is thought of about 20 – 30 %. In this refrigerant centration, the thermal conductivity, viscosity and dielectric constant of nano-oil / refrigerant mixture does not largely change comparing with those without mixing nanoparticles as shown in Figs. 9, 10 and 11. Particularly, regarding dielectric constant, it is a good information for actual use of nano-oil for refrigeration cycles that the dielectric constant hardly changes for nano-oil / refrigerant mixture. However, because the scattering of measured value is large, further precise measurement of the physical properties is needed in the future. Moreover, it is also very important to investigate the effect of nano particles on leakage of refrigerant in the compressor and tribological property for actual use of nano-oil to the refrigerant compressor.

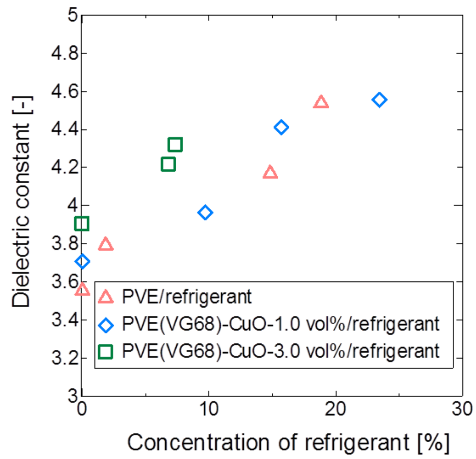

Figure 11: Dielectric constant of PVE-CuO nano-oil / R410A mixture as a function of refrigerant concentration.

6. CONCLUSIONS

Physical properties of PVE-CuO nano-oil such as thermal conductivity, viscosity and dielectric constant were measured under atmospheric condition. In addition, the same properties of PVE-CuO nano-oil / R410A mixture were also measured under pressurized conditions. the volume fractions of CuO nanoparticles in nano-oil were 0.5, 1.0 and 3.0 vol%. The following results were obtained.

(1) Thermal conductivity of nano-oil increases with the volume concentration of nanoparticles. The tendency of the variation of thermal conductivity of PVE-CuO nano-oil has similar to the Hamilton and Crosser model, but the increasing level of thermal conductivity is slightly smaller than that calculated by the Hamilton and Crosser model. Viscosity of nano-oil increases with increasing volume fraction of nanoparticles, the tendency has similar configuration to the Kole equation. The dielectric constant of nano-oil is higher than that of pure oil, and it becomes large with increasing the volume fraction of nanoparticle.

(2) Thermal conductivity, viscosity and dielectric constant of nano-oil / refrigerant mixture increases compared with those without mixing nano particles for low refrigerant concentration. The effect of addition of nanoparticles with pure oil appears to be weaken with increasing refrigerant concentration.

NOMENCLATURE

a	Radius of nanoparticle	(m)
a_a	Effective radius of aggregation of nanoparticles	(m)
k	Thermal conductivity	(W/m·K)
n	Coefficient of particle shape	(–)
η	Viscosity	(mPa·s)
φ	Volume fraction of particles	(–)

Subscript

bf	base fluid
nf	nanofluid
p	particle

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ACKNOWLEDGEMENT

This study was partly supported by JSPS KAKENHI Grant Number JP16K06116.