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Engineering Notes

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Enhanced Heat Transfer Behaviors of New Heat Carrier for Spacecraft Thermal Management

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Introduction

SPACECRAFT in orbit must dissipate tremendous amounts of waste heat from absorbed solar radiation and internal heat sources. One of the primary ways of dispersing thermal energy, a fluid cooling loop, is done through pumping the heat transfer process fluids between the heat exchangers for sources and sinks. In conventional systems, the process fluids with low thermal conductivity are often used as heat carriers and do not meet the development of high compactness and effectiveness of heat systems. The recent innovative technique of suspending metallic or nonmetallic nanoparticles in fluids, or nanofluids, offers the exciting possibility of increased an heat transfer efficiency of thermal control system.[1]

Some experimental investigations have revealed that the nanofluid has superior heat transfer properties to that of conventional pure fluids and fluids with suspended millimeter- or micrometer-sized solid particles.[2–5] Application of the nanofluid to an aerospace thermal control system is expected to exhibit such advantages as reduction of the size and weight of the system and low pumping-power consumption. All of these are especially important for spacecraft.

The purpose of this Note is to demonstrate experimentally the feasibility of the concept of nanofluids for aerospace application. The research efforts to characterize the heat transfer behavior of nanofluids include three main aspects: preparation of the nanofluids, experimental determination of the transport properties of the nanofluids, as well as convective heat transfer and flow characteristics of the nanofluids.

Preparation of Nanofluids for Aerospace Applications

In this Note, the two-step method used to prepare a class of nanofluid is described. The preparation process is shown schematically in Fig. 1. The sample nanofluids consist of copper nanoparticles of about 26-nm-diam and the special process liquid coolant, perflourotriethylamine, used in the spacecraft thermal management system. To prevent aggregation of the suspended nanoparticles, a small amount of fatty acid salt is selected as the dispersant to cover the nanoparticles. The further formation of particle clusters is suppressed by the ultrasonic vibration technique. All of these techniques aim at changing the surface properties of suspended copper particles and reducing the Van der Waals attractive force among the nanoparticles. With this method, several sample nanofluids for possible aerospace applications have been prepared. The dispersion experiments show that stable suspensions of copper nanoparticles in fluids can be achieved.

Transport Properties of Nanofluids for Aerospace Applications

The transient double-hot-wire apparatus is used to measure thermal conductivity of the nanofluids. The apparatus is calibrated by measuring deionized water and mineral oil, which shows the error of the experimental rig to be less than 3% (Ref. 6).

Before the thermal conductivity of nanofluids is measured the thermal conductivity of the pure base fluid used in spacecraft is measured using the same instrument. The experimental results reveal that the pure base fluid inherently has poor thermal properties and is only 22% of the thermal conductivity of water at the same temperature and even lower than that of ethylene glycol at 10°C. Therefore, the potential technologies achieved through adding nanoparticles to improve the thermal conductivity of conventional process fluids are of great interest.

Nanofluids with different particle volume fractions are involved in the experiment to investigate the effect of nanoparticle concentration on the enhanced heat transfer performances of nanofluids. In the present study, the volume fraction of nanoparticles is determined from the mass fraction of nanoparticles. Figure 2 shows the measured thermal conductivity of the sample nanofluids with

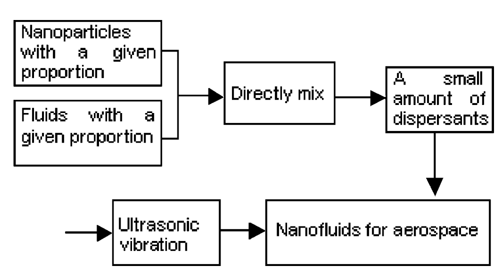

Fig. 1 Preparation process of nanofluid.

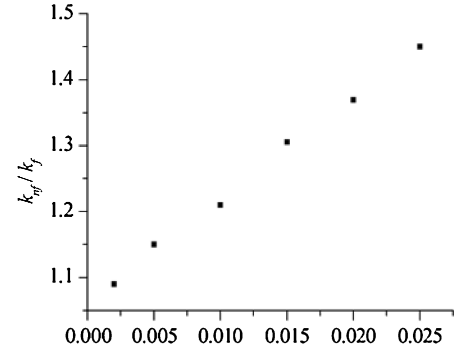

Fig. 2 Thermal conductivity of Cu-process-fluid nanofluid.

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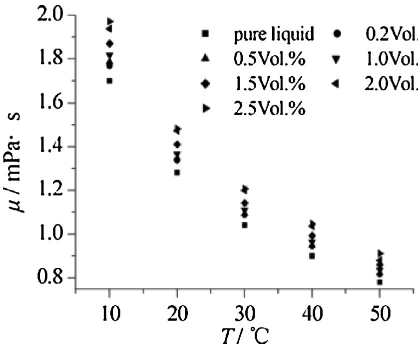

Fig. 3 Viscosity of Cu-process-fluid nanofluids.

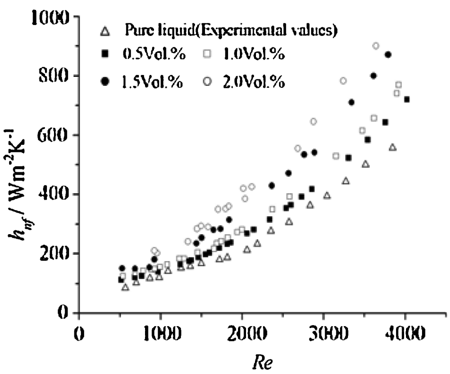

Fig. 4 Convective heat transfer coefficients of Cu-process-fluid nanofluids.

different particle volume fractions at 10°C. The experiments show that the nanofluids have a larger thermal conductivity than pure fluids. The thermal conductivity of the nanofluid becomes remarkable with an increase in the volume fraction of the suspended nanoparticles. For example, the ratio of the thermal conductivity of the nanofluid to that of the pure base fluid varies from 1.09 to 1.45 if the volume fraction of the nanoparticles is increased from 0.2 to 2.5%.

The viscosity of the aforementioned sample nanofluids is measured using a NXE-1 viscometer. Figure 3 shows the viscosity of the nanofluids with different volume fractions of nanoparticles at different temperatures. Obviously, the suspended nanoparticles increase the viscosity of the fluid. The viscosity of the nanofluid increases with the volume fraction of the nanoparticles.

A comparison between the enhancement of thermal conductivity and the increment of viscosity of the nanofluid for aerospace applications shows that the increment of the viscosity of the nanofluid is much lower than the enhancement magnitude of the thermal conductivity of the nanofluid. It is expected that this type of nanofluid is suitable for practical applications in the thermal management system of spacecraft, incurring little penalty in pressure drop.

Convective Heat Transfer and Flow Features of Nanofluids for Aerospace Applications

To apply the nanofluid to practical heat transfer processes for the thermal management of spacecraft, more studies on its flow and heat transfer features are needed. An experimental rig is used to study the convective heat transfer and flow characteristics of the nanofluid for aerospace applications flowing in a tube (shown schematically in Ref. 3). The reliability and accuracy of the experimental system are estimated by using water as the working fluid. The good coincidence between the experimental results and the calculated values from the existing correlation for water in the reference fluid reveals that the uncertainty of the experimental system is less than 4%.

Figure 4 provides the convective heat transfer coefficients of the nanofluids with different Reynolds numbers. The experiments show that the suspended nanoparticles remarkably increase heat transfer

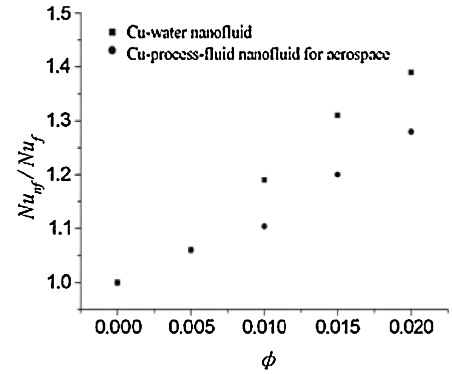

Fig. 5 Comparison between Nusselt number of Cu-process-fluid nanofluids and Cu–water nanofluids.

performance of the base fluid and that the heat transfer coefficients of the nanofluids increase with the volume fraction of nanoparticles. Compared with a pure base fluid, for example, the convective heat transfer coefficient of the nanofluid is increased about 75% for the nanofluid with 2.0 vol.% Cu nanoparticles under the same Reynolds number.

The chaotic movement of nanoparticles plays an important role in heat transfer enhancement. The chaotic movement of nanoparticles will flatten the temperature distribution and make the temperature gradient between the fluid and the wall steeper, which augments heat transfer rate between the fluid and the wall. Evidently, one of the affecting factors of the chaotic movement of nanoparticles is the viscosity of the base liquid. The convective heat transfer coefficient of nanofluids varies with the viscosity of the base liquid. The smaller the viscosity of the base liquid, the larger the convective heat transfer coefficient of nanofluids because the nanoparticles move faster in the lower-viscosity base liquid. This is validated by comparing the measured Nusselt number of the Cu-process-fluid nanofluids to that of the Cu–water nanofluids as shown in Fig. 5 for two kinds of nanofluids containing the same Cu nanoparticles. Because of the viscosity of process fluids for aerospace applications is greater than that of water, the Nusselt numbers of Cu-process-fluid nanofluids is less than that of Cu–water nanofluids for the same particle volume fraction at a given fluid velocity.

As mentioned before, it is improper to apply the conventional correlation for single-phase fluids to the prediction of the Nusselt number of the nanofluid even if the effective transport properties of the nanofluid are used, especially for the high-volume fraction of the nanoparticles. A new correlation is expressed as follows[3]:

$$Nu_{\mathrm{nf}} = c_1\left(1.0 + c_2\phi^{m_1} Pe_d^{m_2}\right) Re_{\mathrm{nf}}^{m_3} Pr_{\mathrm{nf}}^{0.4} \tag{1}$$

where the particle Peclet number, the Reynolds number, and the Prandlt number of the nanofluid are, respectively, defined as

$$Pe_d = u_m d_p / \alpha_{\mathrm{nf}} \tag{2}$$

$$Re_{\mathrm{nf}} = u_m D / \upsilon_{\mathrm{nf}} \tag{3}$$

$$Pr_{\mathrm{nf}} = \upsilon_{\mathrm{nf}} / \alpha_{\mathrm{nf}} \tag{4}$$

where u_m is the mean velocity, D is inner diameter of the tube, υ_{nf} is the viscosity of the nanofluid, d_p is the mean diameter of the nanoparticle, and α_{nf} is the thermal diffusivity of the nanofluid,

$$\alpha_{\mathrm{nf}} = \frac{k_{\mathrm{nf}}}{(\rho c_p)_{\mathrm{nf}}} = \frac{k_{\mathrm{nf}}}{(1-\phi)(\rho c_p)_f + \phi(\rho c_p)_d}$$

With an ensemble of the foregoing experimental data of Nu_{nf} vs ϕ, Pe_d, Re_{nf}, and Pr_{nf}, the coefficients c_1 and c_2, as well as the exponents m_1, m_2, and m_3, are found by data reduction. The convective heat transfer correlation of nanofluids is shown as follows:

$$Nu_{\mathrm{nf}} = 0.0014\left(1.0 + 9.3612\phi^{0.4593} Pe_d^{0.001}\right) Re_{\mathrm{nf}}^{1.0259} Pr_{\mathrm{nf}}^{0.4} \tag{5}$$

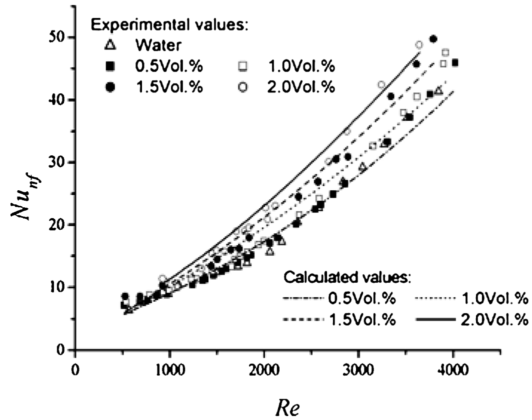

Fig. 6 Comparison between measured data and calculated Nusselt number of Cu-process-fluid nanofluids.

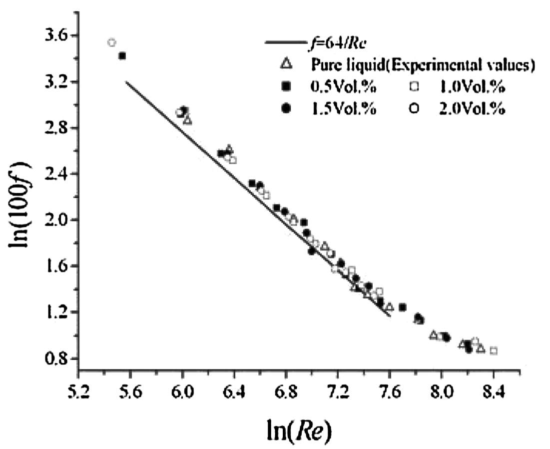

Fig. 7 Friction factors of Cu-process-fluid nanofluids.

Figure 6 shows the calculated results of the nanofluids with expression (5). Calculated and experimental results show relatively good agreement.

It is necessary to determine the flow resistance of nanofluids in addition to the heat transfer enhancement feature. Figure 7 shows the friction factors as a function of the Reynolds number. Figure 7 shows that the friction factors of the dilute nanofluids are almost equal to those of water under the same Reynolds number and do not increase with the volume fraction of nanoparticles. Compared with water, no significant augmentation in pressure drop for the nanofluid is found in all runs of the experiment, which reveals that dilute nanofluids will not cause an extra penalty in pump power.

Conclusions

A new heat carrier, namely, a nanofluid, has been prepared by directly suspending the nanoscaled Cu particles in the base process fluid used in spacecraft. The transport properties and enhanced heat transfer behaviors of this heat carrier have been experimentally investigated.

The experimental results have shown that the suspended nanoparticles remarkably increase the thermal conductivity and the convective heat transfer performance of the base fluid used in spacecraft. The increment of the viscosity of the heat carrier is much lower than the enhancement extent of the thermal conductivity of the heat carrier. The volume fraction of the nanoparticles is the main factor affecting the enhanced heat transfer behavior of the heat carrier. The heat transfer feature of the new heat carrier increases with the volume fraction of nanoparticles. Such a new heat carrier has great potential applications for the thermal management purposes of spacecraft.

Acknowledgments

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