Assessment of the Use of Nanofluids in Spacecraft Active Thermal Control Systems

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Abstract

The addition of metallic nanoparticles to a base heat transfer fluid can dramatically increase its thermal conductivity. These nanofluids have been shown to have advantages in some heat transport systems. Their enhanced properties can allow lower system volumetric flow rates and can reduce the required pumping power. Nanofluids have been suggested for use as working fluids for spacecraft Active Thermal Control Systems (ATCSs). However, there are no studies showing the end-to-end effect of nanofluids on the design and performance of spacecraft ATCSs.

In the present work, a parametric study is performed to assess the use of nanofluids in a spacecraft ATCSs. The design parameters of the current Orion capsule and the tabulated thermophysical properties of nanofluids are used to assess the possible benefits of nanofluids and how their incorporation affects the overall design of a spacecraft ATCS. The study shows that the unique system and component-level design parameters of spacecraft ATCSs render them best suited for pure working fluids. The addition of nanoparticles to typical spacecraft thermal control working fluids actually results in an increase in the system mass and required pumping power.

Assessment of the Use of Nanofluids in Spacecraft Active Thermal Control Systems

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The addition of metallic nanoparticles to a base heat transfer fluid can substantially increase its thermal conductivity. These nanofluids have been shown to have advantages in some heat transport systems. Their thermal properties allow the system volumetric flow rate to be reduced, thus reducing the required pumping power. Nanofluids have been suggested as working fluids in spacecraft Active Thermal Control Systems (ATCSs). However, spacecraft ATCSs are unique in that they have stringent temperature control requirements and use specialized heat transfer devices. In the present work, a parametric study was performed to assess the use of nanofluids in spacecraft ATCSs. The tabulated thermophysical properties of various nanofluids, the design requirements of NASA's Orion ATCS and the performance parameters of its key heat transfer components were used to assess the effects of the incorporation of nanofluids. The study shows that the unique system and component-level design parameters of spacecraft ATCSs do not lend themselves to the use of nanofluids. The addition of nanoparticles to typical spacecraft internal flow loop working fluids actually results in an increase in either the system mass or the required pumping power, the opposite of the hoped-for effect. The intermediate results obtained in the study also suggest that that the addition of nanoparticles to an external ATCS loop is not likely to result in a significant overall system benefit.

Nomenclature

A	=	area
c	=	constant
c_p	=	specific heat
d	=	tubing inner diameter
f	=	Darcy-Weisbach friction factor
h	=	convective coefficient
k	=	fluid thermal conductivity
l	=	tubing length
L	=	head loss coefficient
$\dot{m}$	=	mass flow rate
Nu	=	Nusselt number
Pr	=	Prandtl number
Q	=	system heat load
Re	=	Reynolds number
T	=	temperature
UA	=	heat exchanger heat transfer coefficient
V	=	average flow velocity
Δp	=	pressure difference
ΔT	=	temperature difference
ε	=	radiator emissivity
η	=	radiator fin efficiency
μ	=	dynamic viscosity

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ρ	=	density
σ	=	Stefan-Boltzmann constant

subscripts

avg.	=	average
bf	=	base fluid – 60/40 ethylene glycol/water
comp.,fittings, CVs	=	in components, fittings, and control valves
HFE 7000	=	HFE 7000 coolant
H/X	=	in heat exchanger
ht	=	heat transfer
L	=	laminar
nf	=	nanofluid – base fluid with added nanoparticles
tubing	=	in tubing
T	=	turbulent
Δp	=	pressure difference
∞	=	radiator sink

I. Introduction

ACTIVE Thermal Control Systems (ATCSs) are used on spacecraft to remove waste heat from electronics and habitable volumes. They can use one loop or two loops in series. In single loop systems, a single pumped loop collects waste heat from the crew cabin and spacecraft components and rejects it to the environment. Dual loop systems use separate loops inside and outside of the crew cabin. The two loops are connected by an interloop heat exchanger.

Normally redundant ATCSs are used to provide fault tolerance. That is, a spacecraft using a single loop system would have multiple parallel loops. A spacecraft using a two loop system would have multiple separate pairs of internal and external loops. The discussion in the present work assesses a single set of redundant loops.

ATCSs on US human spacecraft have historically used commonly available working fluids as listed in Table 1. The table lists the fluid used in the internal pumped loop and the fluid used in the external pumped loop – where applicable[*].

Early in the US human space program, working fluid toxicity was not an overriding concern and single loop systems used a fluid with good thermal performance and a low freezing point. With the advent of the Space Shuttle, lack of toxicity became a requirement for any working fluid used inside the spacecraft cabin. This led to the use of two loop systems where a non-toxic high freezing point fluid loop flows through the crew cabin. An interloop heat exchanger transfers the spacecraft waste heat to an external loop containing a low freezing point fluid.

It has been suggested that adding nanoparticles to a spacecraft ATCS might increase its performance, decrease its mass, and reduce its pumping power[1]. However, there have been no end-to-end studies that investigate the effects of adding nanoparticles to spacecraft ATCSs. In the present work, a parametric assessment was performed. The tabulated thermophysical properties of various nanofluids, the design requirements of the current Orion ATCS and the performance parameters of its key heat transfer components were used to assess the effects of incorporating nanofluids. Because minimizing mass and power is the main goal of spacecraft design, the nanofluids' benefits were assessed based on their effect on the overall mass and required pump power of the ATCS.

Table 1. Human Spacecraft Active Thermal Control System Working Fluids

Spacecraft	Internal Pumped Loop	External Pumped Loop
Gemini	silicone ester oil (single loop)	
Apollo Command Module	water/ethylene glycol mixture (single loop)	
Apollo Lunar Module	water/ethylene glycol mixture (single loop)	
Skylab	silicone ester oil (single loop)	
Space Shuttle	water	Freon-21
International Space Station	inhibited water	anhydrous ammonia
Orion	water/Dowfrost HD (inhibited propylene glycol) mixture	HFE 7000

[*] The Mercury spacecraft used air cooling only, so it is not listed.

II.   Overview of Orion's ATCS

Orion's ATCS is a two loop system as shown in Figure 1. The loop that circulates through the pressurized volume contains a 50/50 mixture of water and Dowfrost HD inhibited propylene glycol. The external loop uses HFE 7000. A ruffled fin compact heat exchanger connects the two loops.

The water/Dowfrost HD fluid loop sequentially cools the cabin air heat exchanger, internal coldplates, and external coldplates.   The coldplates cool the spacecraft avionics and batteries. Coolant is provided to the cabin air heat exchanger at a setpoint temperature of 281.4 K (47°F) – a temperature derived from the cabin humidity control requirements. This setpoint is maintained using an internal bypass control. Owing to the low battery coldplate heat flux, the fluid exit temperature design limit is equivalent to the maximum allowable battery baseplate temperature of 303.2 K (86°F).

The water/Dowfrost HD transfers its heat to the external fluid loop at the interloop heat exchanger. The external fluid loop rejects the waste heat to the radiator array.   A regenerator bypass[2] is used to maintain the desired HFE 7000 return

Figure 1. : Simplified Orion Dual Loop ATCS – One of Two Loop Pairs

temperature over the range of vehicle heat loads and radiator environments. In the event that the radiator capacity is exceeded, an evaporative heat sink vents water or ammonia to provide supplemental cooling.

For the purposes of the present study, the spacecraft design point is considered. This is the condition where the required cooling needs are only just met with:
- the internal bypass leg closed,
- the regenerator fully bypassed,
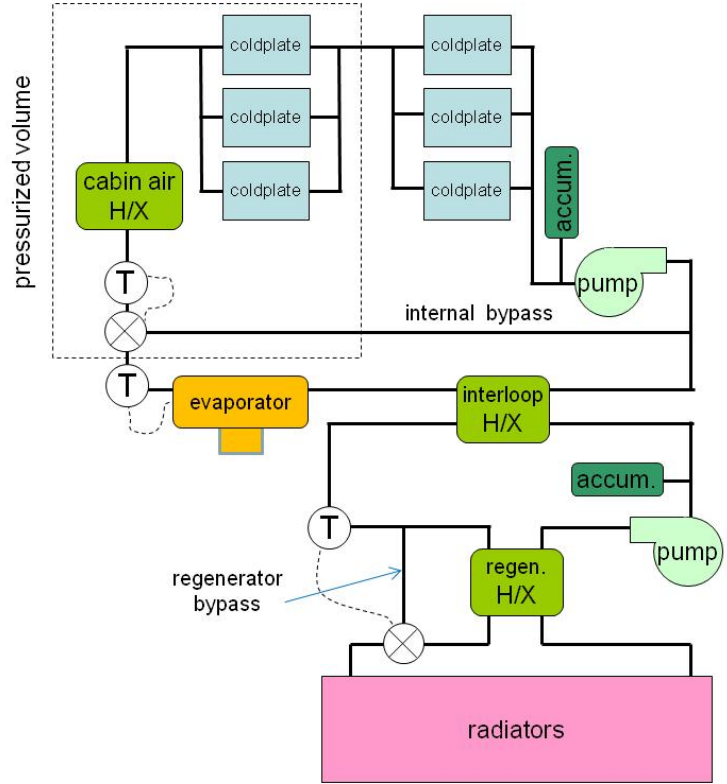- and the evaporator inactive.

III.   Study Methodology

To assess the benefits of using nanofluids as spacecraft ATCS working fluids, a detailed parametric analysis was performed using the Orion internal[†] system as a baseline. The literature contains thermophysical property data for nanofluids composed of metallic nanoparticles added to a water/ethylene glycol mixture, so a conceptual design of an Orion internal loop using 60% ethylene glycol and 40% water was used as the baseline[‡]. The performance of the nanofluids was assessed in two ways: 1) by calculating the change in system mass while maintaining the same pumping power and 2) by calculating the change in pump power while maintaining the same system mass.

[†] Because there are no available property databases for HFE 7000-based nanofluids, the external loop was not addressed specifically in this study. However, the intermediate results for the internal loop study point toward a likely result for the external loop, as will be discussed in the Results section.

[‡] The properties for ethylene glycol and water mixtures will differ from those of the inhibited propylene glycol and water mixture used by Orion, but the overall trends with nanoparticles are expected to be similar owing to the similar nature of the base fluids.

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Table 2. Properties of 60:40 Water/Ethylene Glycol with Nanoparticles at 298K

Nanoparticle	Volumetric Concentration	Density kg/m^3	Viscosity kg/(m s)	Specific Heat J/(kg K)	Thermal Conductivity W/(m K)	Prandtl No.	Volumetric Specific Heat kJ/(m^{3}K)
none	0.00	1084	0.00423	3148	0.3729	35.75	3412
Aluminum Oxide (Al$_2$O$_3$)	0.01	1109	0.00474	3071	0.4104	35.45	3405
	0.02	1134	0.00539	2997	0.4203	38.45	3399
	0.03	1159	0.00614	2926	0.4311	41.67	3392
	0.04	1184	0.00699	2859	0.4423	45.17	3385
	0.05	1209	0.00796	2794	0.4538	48.97	3379
	0.06	1235	0.00906	2731	0.4657	53.12	3372
Copper Oxide (CuO)	0.01	1138	0.00489	2999	0.4123	35.59	3412
	0.02	1192	0.00615	2863	0.4243	41.49	3413
	0.03	1246	0.00773	2739	0.4362	48.54	3413
	0.04	1300	0.00971	2625	0.4480	56.92	3414
	0.05	1354	0.01224	2521	0.4600	66.90	3414
	0.06	1409	0.01534	2424	0.4721	78.79	3415

Aluminum oxide and copper oxide nanoparticles at concentrations ranging from 0 to 6% by volume were assessed. The fluid properties were taken at 298K (76.7°F), a temperature where properties are available in the existing databases[3,4], that is approximately equal to the average inner loop fluid temperatures.   The properties for each nanofluid are shown in Table 2.

The baseline design was developed from the following Orion ATCS design requirements and component performance parameters:
- Loop heat load = 2.5 kW (for one of the two ATCS loop pairs)
- Internal loop setpoint temperature of 281.5 K (47°F)
- Maximum internal loop temperature of 303.2 K (86°F).
- Internal loop transport length of 50 m (162.5 ft)
    - 0.035 in wall titanium tubing, which was assumed to be available in any needed diameter – not just in stock tube sizes. The tubing density was taken as 4488 kg/m^3 (280.2 lbm/ft^3).
- The total Orion internal loop pressure drop of 172 kPa (25psid) was apportioned as:
    - 30% from tubing friction,
    - 60% from components (other than the heat exchanger), valves, and fittings
    - 10% from the interloop heat exchanger
- The product of mass flow rate and specific heat is the same in the internal and external loops
- The temperature difference across the counterflow interloop heat exchanger at full load is 3.9 K (7°F) and is uniform
    - 1/5th of the temperature drop is across the water/Dowfrost HD side
    - 4/5th of the temperature drop is across the HFE 7000 side
- The radiator parameters were
    - Sink temperature of 233.15 K (-40°F)
    - Surface emissivity of 0.9
    - Fin efficiency of 0.95
        - Includes the minor effect of the internal film heat transfer resistance
    - Specific mass was based on the space shuttle value of 5.85 kg/m^2 (1.20 lbm/ft^2) - the Orion radiator design details had not been finalized at the time of the present work.

The study baseline design for the 60/40 mixture of ethylene glycol (EG) and water yielded:
- Mass flow rate of 0.0366 kg/s (290 lbm/hr) in the water/EG loop[§]
- Volumetric flow rate of 3.38x10-5 m³/s (4.29 ft³/hr)
- Tubing internal diameter of 8.64 mm (0.34 in)
- Radiator area of 12.94 m² (139.285 ft²)
  - based on the average radiator fluid temperature.

The effects of nanofluids were assessed parametrically by calculating the change in tubing mass, fluid mass, accumulator mass, radiator mass, and pump power caused by the substitution of the nanofluid. The detailed study methodology and results are discussed next.

1. Constant Pump Power Method

The first method used in the study assessed the change in overall system mass given a constant pump power. Since the volumetric specific heat of the base fluid and nanofluids is the same within 1%, the loop volumetric flow rate is taken to be the same for all the cases. Thus, constant pump power implies that the internal loop pressure drop does not change with the addition of nanoparticles.

The pressure drop, Δp, through the system was calculated by summing the pressure drop through the tubing, components, fittings, and control valves, plus the heat exchanger:

$$\Delta p = \Delta p_{tubing} + \Delta p_{comp.,fittings\,\&\,CVs} + \Delta p_{H/X} \tag{1}$$

The tubing pressure drop is calculated using standard methods

$$\Delta p_{tubing} = f\frac{l}{d}\frac{1}{2}\rho V^2 \tag{2}$$

where f is the Darcy-Weisbach friction factor, l is the flow path length of 50 m (132.5 ft), d is the tube inner diameter, ρ is the fluid density, and V is the average flow velocity.

The component, fitting, and control valve pressure drop is calculated using a constant head loss, L, which was taken from the base fluid calculation

$$\Delta p_{comp.,fittings\,\&CVs} = L\frac{1}{2}\rho V^2 \tag{3}$$

The heat exchanger pressure drop with the nanofluid, Δp_{nf}, was calculated based on the pressure drop with the base fluid, $\Delta p_{bf,}$

$$\Delta p_{nf} = \frac{\Delta p_{nf}}{\Delta p_{bf}}\Delta p_{bf} \tag{4}$$

The subscripts bf and nf refer to the base fluid and the nanofluid, respectively.

The ratio of heat exchanger pressure drops was calculated for both laminar and turbulent flows from compact ruffled fin heat exchanger performance data[5]. For turbulent flow, the Darcy-Weisbach friction factor is:

$$f = c_{\Delta p,T}Re^{-0.442} \tag{5}$$

and for laminar flow:

$$f = \frac{c_{\Delta p,L}}{Re} \tag{6}$$

[§] The internal loop mass flow rate was calculated using $Q = \dot{m}c_p\Delta T$ where Q is the heat transferred across the interloop heat exchanger, $\dot{m}$ is the mass flow rate of fluid in the loop, c_p is the specific heat of the fluid, and ΔT is the temperature rise through the loop (21.7°C or 39°F).

where Re is the Reynolds number of the fluid and $c_{\Delta p,T}$ and $c_{\Delta p,L}$ are pressure drop constants for turbulent and laminar flow, respectively. By using the ratio of the nanofluid and base fluid pressure drops, $\Delta p_{nf}/\Delta p_{bf}$, as the key variable, the heat exchanger characteristic diameter, flow velocity, and $c_{\Delta p,T}$ and $c_{\Delta p,L}$ cancel.

So, for turbulent flow:

$$\frac{\Delta p_{nf}}{\Delta p_{bf}} = \left(\frac{\dot{m}_{nf}\mu_{bf}}{\dot{m}_{bf}\mu_{nf}}\right)^{-0.442} \frac{\rho_{bf}}{\rho_{nf}} \left(\frac{\dot{m}_{nf}}{\dot{m}_{bf}}\right)^2 \tag{7}$$

And for laminar flow:

$$\frac{\Delta p_{nf}}{\Delta p_{bf}} = \left(\frac{\dot{m}_{bf}\mu_{nf}}{\dot{m}_{nf}\mu_{bf}}\right) \frac{\rho_{bf}}{\rho_{nf}} \left(\frac{\dot{m}_{nf}}{\dot{m}_{bf}}\right)^2 \tag{8}$$

where $\dot{m}$ is the mass flow rate and μ is the viscosity.

To size the tubing for a given nanofluid, the heat exchanger pressure drop was first calculated. The tube diameter was then adjusted to maintain the same overall pressure drop of 172.37kPa (25psi) with the same component, fitting, and control valve loss coefficient and flow length as the baseline system. Once the tube diameter was finalized and the new loop volume was known, the additional required accumulator volume and mass was calculated[**].

The addition of the nanoparticles changes the performance of the interloop heat exchanger, changing the temperature of the external fluid loop, and changing the required radiator size. The change in heat exchanger performance caused by the nanofluids was calculated using a methodology similar to that used for the heat exchanger pressure drop.

The Nusselt number for the compact ruffled fin heat exchangers[5] is:

$$Nu = c_{ht,T} \, Re^{0.595} Pr^{1/3} \tag{9}$$

for turbulent flow and

$$Nu = c_{ht,L} \tag{10}$$

and for laminar flow. Here Pr is the Prandtl Number of the fluid and $c_{ht,T}$ and $c_{ht,L}$ are heat transfer constants for turbulent and laminar flows, respectively.

The change in the heat exchanger convection coefficient is calculated from

$$\frac{h_{nf}}{h_{bf}} = \frac{k_{nf}}{k_{bf}} \left(\frac{\dot{m}_{nf}\mu_{bf}}{\dot{m}_{bf}\mu_{nf}}\right)^{0.5952} \left(\frac{Pr_{nf}}{Pr_{bf}}\right)^{1/3} \tag{11}$$

for turbulent flow and

$$\frac{h_{nf}}{h_{bf}} = \frac{k_{nf}}{k_{bf}} \tag{12}$$

for laminar flow. Here k is the thermal conductivity of the fluid.

These convection coefficient ratios were used to calculate the change in heat exchanger performance. The overall heat exchanger heat transfer coefficient with the base fluid, $UA_{H/X,bf}$, is 642 W/K (1218 BTU/hr°F) based on the Orion loop performance. $UA_{H/X,bf}$ can be expressed as the sum of the heat transfer on the internal loop side, UA_{bf}, and on the HFE 7000 side, $UA_{HFE\,7000}$.

[**] The required increase in accumulator volume was calculated by comparing the volumetric change of the nanofluid system to the baseline system from the sink temperature of 233.15K (-40°F) to the average loop temperature of 218.43K (66.5°F). The increase in accumulator volume resulted in additional liquid inventory mass plus accumulator mass. The additional accumulator mass was taken as equal to the product of the base fluid density and the accumulator volume change.

$$UA_{H/X,bf} = \frac{1}{\frac{1}{UA_{bf}} + \frac{1}{UA_{HFE\ 7000}}} \tag{13}$$

Based on the study assumptions listed previously, the base fluid overall heat transfer coefficient is four times the HFE 7000 overall heat transfer coefficient, so UA_{bf}=3216 W/K (6093 BTU/hr°F), and $UA_{HFE\ 7000}$=803 W/K (1523 BTU/hr°F).

The heat exchanger performance with the nanofluid, $UA_{H/X,nf}$, be calculated from

$$UA_{H/X,nf} = \frac{1}{\left(\frac{h_{bf}}{h_{nf}}\right)\frac{1}{UA_{bf}} + \frac{1}{UA_{HFE\ 7000}}} \tag{14}$$

This allows the nanofluid heat exchanger temperature difference, the average radiator fluid temperature, and the new required radiator area to be calculated.

The average HFE 7000 temperature, $T_{HFE\ 7000,avg.}$, is the internal loop average temperature less the heat exchanger temperature drop.

$$T_{HFE\ 7000,avg.} = \frac{281.4K + 303.2K}{2} - \frac{Q}{UA_{H/X,nf}} \tag{15}$$

where Q is the system heat load of 2.5 kW. The required radiator area, A_{rad}, is calculated from radiation principles

$$A_{rad} = \frac{Q}{\varepsilon\eta\sigma\left(T^4_{HFE\ 7000,avg.} - T^4_{\infty}\right)} \tag{16}$$

where ε is the radiator emissivity, η is radiator fin efficiency, σ is the Stefan-Boltzman constant, and T_{∞} is the effective sink temperature.

The change in tube and accumulator size, required fluid volume, and radiator area was then used to find the overall change in the mass of the system caused by the addition of nanoparticles.

2. Constant System Mass Method

The second method assessed the change in required pump power for a nanofluid system with the same mass as the base fluid system. Here the same constitutive equations were used as in the constant pump power method, but changes in radiator mass were offset by changes in the internal loop mass (including the accumulator).

For a given nanofluid, the change in radiator performance from the constant pump power method was first used to calculate the change in radiator mass. This change in mass was then applied (with opposite sign) to the internal loop and used to calculate the new tubing diameter.

Since the volumetric flow rate was invariant throughout the analysis, the change in pump power is proportional to the change in internal loop pressure drop.

Results

A. Constant Pump Power
1. Interloop Heat Exchanger Performance

Adding nanoparticles did not always improve the performance of the innerloop heat exchanger. Figure 2 shows the change in the hot side convection coefficient with the addition of nanoparticles. The laminar flow heat transfer improves substantially with the addition of nanoparticles. For turbulent heat transfer, small amounts of nanoparticles improve the heat transfer, but larger amounts
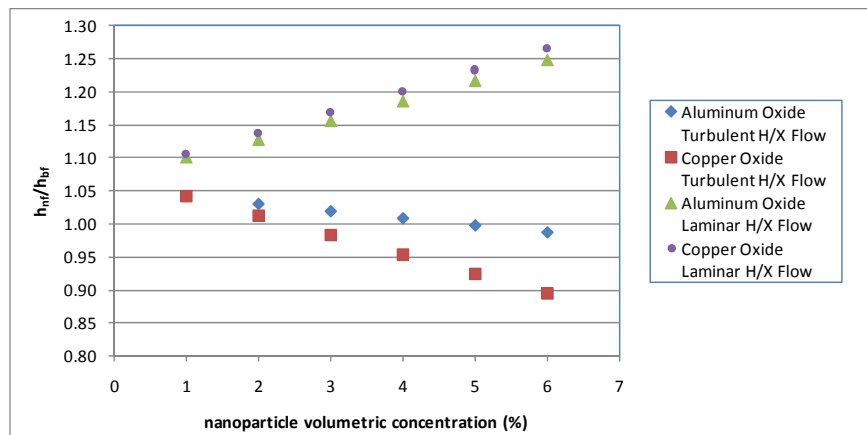
Figure 2. Heat Exchanger Hot Side Convection Coefficient – Constant Pump Power

reduce it. The higher nanofluid viscosity decreases the turbulent Reynolds number and lowers the convection coefficient.

2. Radiator Area

While the most of the nanofluid combinations improved the performance of the interloop heat exchanger, the improvement occurred on the high performance internal loop side (which has only 1/5th of the overall temperature drop). The overall effect on radiator area was therefore minor. Figure 3 shows the radiator area required to reject 2.5kW. The best performing nanofluid generated less than a 0.4% decrease in radiator area (0.05 m^2 or 0.4 ft^2).

3. Radiator Mass

The addition of nanofluids resulted in only minor changes in radiator mass. Figure 4 shows the radiator mass corresponding to the radiator areas in Figure 3. The maximum savings was 0.3 kg (0.66 lbm), less than 0.4% of the radiator mass.

4. Tubing Diameter

The addition of nanofluids uniformly resulted in larger tubing inner diameter to maintain the same overall loop pressure drop. The higher density and viscosity of the nanofluids required lower loop fluid velocities to meet the pressure drop targets. Figure 5 shows the tube inner diameters for a total loop pressure drop of 172.37 kPa (25 psi). It shows that the tube diameter must be increased by as much as 30% to accommodate the nanofluid while maintaining the overall system pressure drop.

5. Overall System Mass

The overall change in system mass resulting from the addition

Figure 3. Radiator Area Required to Reject 2.5kW – Constant Pump Power

Figure 4. Radiator Mass Comparison – Constant Pump Power

Figure 5. Tube Inner Diameter for Constant Pressure Drop – Constant Pump Power

of nanoparticles to the internal loop is shown in Figure 6. The additional mass resulting from the larger required tube diameter more than offsets the radiator mass savings. None of the nanofluids assessed for the constant pump power case resulted in a system mass savings.
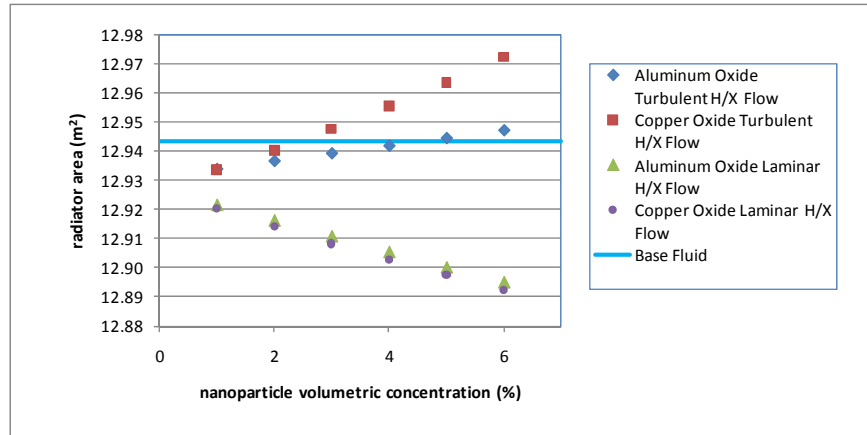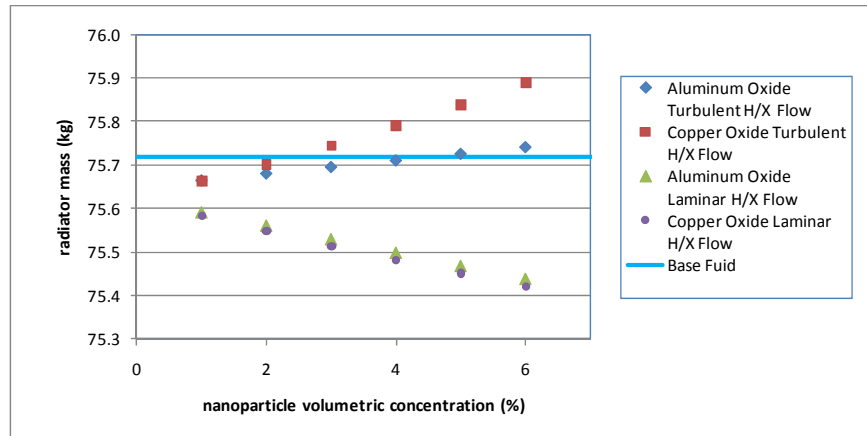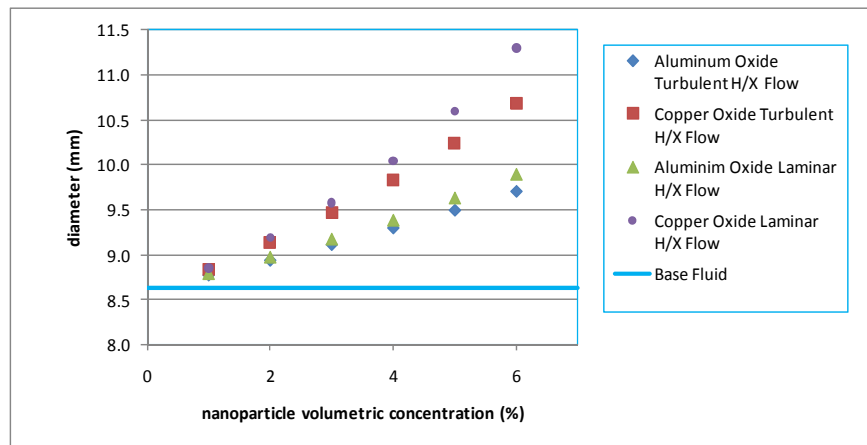
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B. Constant System Mass

When the constant system mass analysis method was used, the higher density of the nanofluid almost always resulted in smaller diameter tubing for the internal loop. The tube inner diameters for a constant system mass are shown in Figure 7.

1. Pump Power

The smaller tube diameters and the increased pressure drop in the heat exchanger lead to a greater pressure drop in the internal loop. The nanofluids' higher density and viscosity plus the smaller tube diameter result in much higher pressure drop and associated pump power. The calculated increase in pump power is shown in Figure 8. All the nanofluid pump powers are higher than for the baseline system. The highest concentrations of nanoparticles result in between a 60 and 200% increase in the pump power for the constant mass system.

Figure 6. Overall Change in ATCS Mass – Constant Pump Power
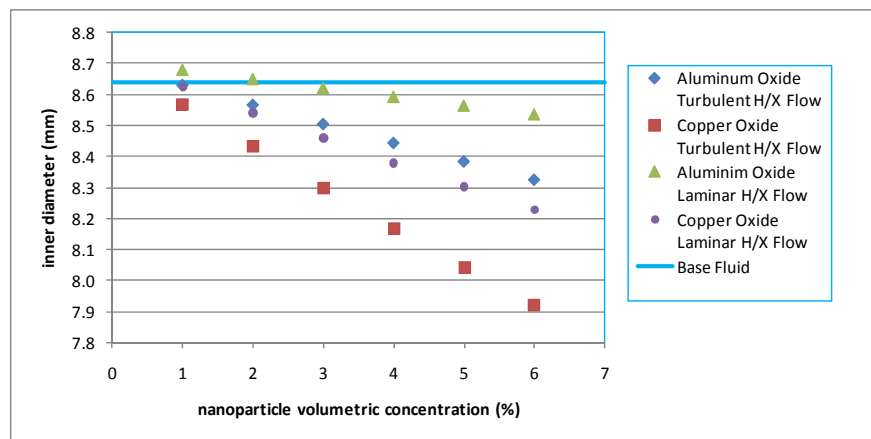
Figure 7. Tube Inner Diameter - Constant System Mass

C. Summary

For both the constant power case and the constant mass case, the addition of nanoparticles to the internal thermal control loop did not result in a better system design. The rigid setpoint and maximum temperature requirements common to all spacecraft ATCSs do not allow a decrease in the system volumetric flow rate with the addition of nanoparticles. The increased pressured drop caused by the higher density and viscosity of the nanofluid requires either larger, heavier lines or higher pump power. These considerations more than offset the marginally smaller radiator that

Figure 8. Pump Power Ratio - Constant System Mass

results from enhanced heat transfer in the interloop heat exchanger. Based on the result of the detailed analysis, we conclude that nanofluids are not a benefit in spacecraft internal fluid loops.

D. Nanofluid Use in the External System

The main reason that nanofluids do not offer an advantage when used in the internal ATCS is that they only marginally improve the interloop heat exchanger performance. Most of the temperature drop in the heat exchanger
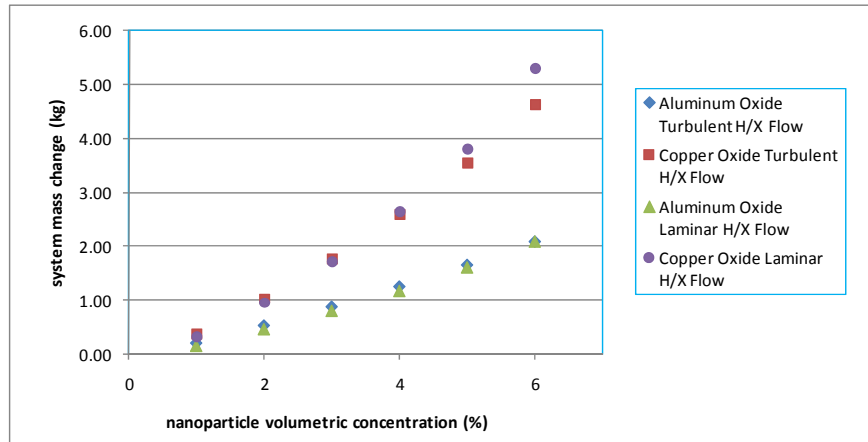
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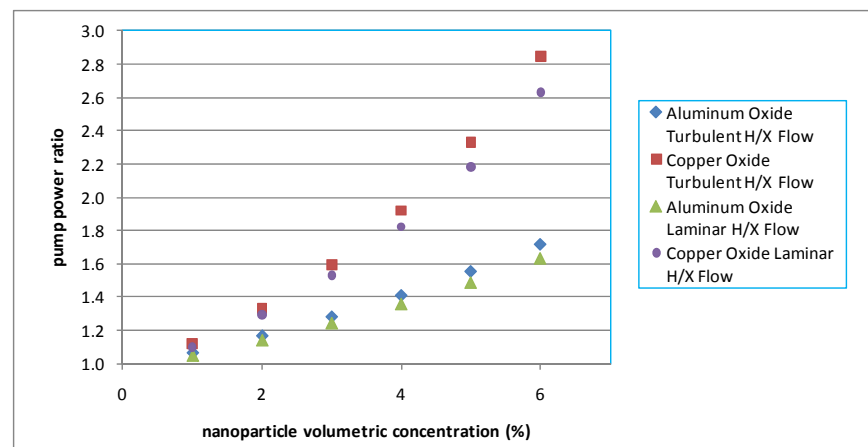is on the external fluid side. If nanoparticles were added to the external loop of a spacecraft ATCS, they could have a greater effect on the interloop heat exchanger performance and resulting radiator area. The potentially larger radiator mass savings might lead to an overall system benefit.

Because there is no thermophysical property data for nanofluids based on HFE 7000, we cannot perform an end-to-end study to assess this case. However, the results of the internal loop nanofluids study provide a means to predict the likely end-to-end results.

The maximum possible improvement that might occur in the case where nanofluids did improve the interloop heat exchanger performance can be bounded. If the heat transfer coefficient on the HFE 7000 side increased by 50%[††] with the addition of nanoparticles, the overall heat exchanger temperature drop would decrease from 3.9 to 2.8 K (7 to 5.1°F). This would shrink the radiator mass by 2.6%, saving 2.0 kg (4.4 lbm). This small mass savings would be at least partially offset by the larger fluid lines (for a constant pump power system) or the higher pumping power of a constant mass system.

A property database for HFE 7000/nanoparticle mixtures would be required to provide a definitive assessment. However, given the low upper limit of the radiator mass savings, it appears that the addition of nanoparticles to the external loop is unlikely to result in a significant overall system benefit.

Conclusions

The effect of using nanofluids in a spacecraft active thermal control system was assessed from a system level perspective. A detailed analysis based on the Orion thermal system specifications, requirements, and component performance showed that the addition of nanofluids to the *internal* fluid loop does not result in mass or power benefits. In fact, the addition of nanoparticles to the internal fluid loop results in a system that is heavier or uses more pump power than the baseline system. The intermediate results obtained in the study also suggest that that the addition of nanoparticles to the *external* loop would not be likely to result in a significant overall system benefit.

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[5]Kays, W. M., and London, A. L., *Compact Heat Exchangers*. 3rd ed. McGraw-Hill, New York: 1984.

[††] This is twice the maximum of 27% found in the present study for the internal loop.