SURVEILLANCE SYSTEM HEAT TRANSFER ENHANCEMENT USING SINGLE-PHASE FLOW WITH NANOFLUID

Conference Paper · September 2012

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Abstract

Following today's needs for improvement on heat transfer, new technologies and innovative solutions must be found in order to meet current requirements for both active and passive thermal control. Independently on the application, there has been substantial growth on the heat fluxes that need to be dissipated, which require different approaches from designers as well as manufacturers of heat exchangers and heat management devices, especially those designed for defense purposes. With the increase of heat dissipation needs, conventional designs are not suitable due to several factors such as operation in hostile environments, high density of electronics that need their temperature to be controlled, which require innovative designs. In such cases, the application of nanofluids can contribute to give designers more degrees of freedom to face the project's requirements. The subject of this article is related to a surveillance system designed for defense purposes, which needs to dissipate high levels of heat loads. For this present investigation, a single-phase forced circulation loop has been considered to promote the thermal management of up to 50 kW of heat, being dissipated to the environment by a fan cooling system. Considerations are made regarding the use of nanofluid, which show that with an addition of 20% by mass of copper nanoparticles to the base fluid (water), enhancements of 12% on the heat transfer coefficients are achieved but the increase on the pressure drop is around 32%. However, the substantial gain on the overall thermal management indicates that the use of a nanofluid for this special application needs to be carefully considered.

Introduction

The needs for thermal management have increased dramatically over the last decade and the prediction is that a steeper increase is yet to come for the next years. Such an increase is directly related to more powerful electronics used for data processing in high-tech equipments used for satellites and defense purposes. As the current thermal management devices using single and two-phase flow are reaching their nominal limits, new and innovative solutions need to be found in order to promote the thermal control for the next generation of equipments. Considering previous experiences, current and future thermal management needs, the use of nanofluids is becoming inevitable.

Even though nanofluid application is a relative recent area of investigation with promising results for thermal control devices, many applications are considering its use as a potential solution for the constant growth on the heat dissipation needs. A nanofluid is a fluid in which microscopic or nanoparticles are held in suspension, totally dissolved in the base fluid. The direct effect is to improve the thermal conductivity of the fluid, which is known, in some cases, to be increased by 20% when an addition of 5% by mass of solid nanoparticles is present in the base fluid, depending on the nanoparticles' material used (Koo and Kleinstreuer, 2004). Nanofluids are composed of a regular base fluid (like water, for example) with an addition of solid nanoparticles with sizes below 100 nm mixed at a fraction of the base fluid's mass. Nanofluids were early presented by Xuan and Li (2000) and Xuan and Roetzel (2000) and have been extensively investigated over the last years with important contributions to several areas, like aerospace, electronics and industry, even though the application on those areas is still in the beginning. Some examples for aerospace applications have been presented focusing on using nanofluids in single-phase and passive thermal control systems using heat pipes, as presented by Riehl and Santos (2011). In this case, the heat source temperature can be kept at lower levels when compared to regular working fluid application, which leads to the possibility of using the nanofluid to dissipate higher levels of heat.

Upon using single-phase cooling systems, the heat transfer can be enhanced as the nanoparticles addition to the base fluid is highly influenced by the presence of more liquid. When the application shows that more vapor is presented, the nanoparticles addition to the base fluid do not show important enhancement on the heat transfer process. Since in aerospace the use of passive thermal control devices is important and their sizes and footprints are a major issue due to limited area available, the use of nanofluids present to be an important approach to enhance the heat transfer capability of heat pipes and loop heat pipes systems, which has already been proven in laboratory conditions, but still requires a full qualification program for space application. Similar investigation has also been performed by Alizad et al (2012) where it showed that smaller sizes heat pipes can be used when operating with nanofluids. Other applications are related to the use of nanofluids in regular heat exchanger devices already installed in industries in order to enhance their performance in face of the increase of heat dissipation needs (Leong et al., 2012).

Many other interesting applications can be found for nanofluids, such as LED thermal management. Since it is well known that LED is the leading technology for the future of lighting and other electronic applications, its thermal control needs to be properly addressed as at least 80% of the energy designated to the LED is rejected as heat. In this case, an adequate and refined interface between the LED and a heat sink (that could be a cold plate or an array of heat pipes) must be present in order to dissipate as much heat as possible. This is very important to be considered because even a high efficient heat sink cannot dissipate the necessary heat from a LED system if its interface is not good enough. Today, it is usually applied a thermal paste (also called heat sink compound), which is a silicon based paste with high thermal conductivity. However, even the most effective heat sink compound will present thermal conductivities around 1 ~ 1.2 W/m-K. By adding a mass fraction of solid copper nanoparticles of 10% on the compound, its thermal conductivity can be enhanced by 30%, which can be a significant improvement for the thermal management required by the LED array. Such improvements find correlation to the work published recently by Fan and Wang (2011). Several other investigations related to nanofluids applications have been conducted with important contributions to many areas (Ebrahimnia-Bajestan et al., 2011; Ghadimi et al., 2011).

An important application for today's needs for heat dissipation is related to surveillance systems designed for defense purposes. As more compact and powerful defense equipments are necessary, higher heat fluxes need to be properly addressed efficiently. Considering that the systems usually operate with single-phase flow, more efficient thermal management devices need to be designed and the use of nanofluids can be a powerful solution. Thus, considering the need for designing a reliable and effective thermal management system that need to operate in hostile environments, with potential use of nanofluid, this article presents an analytical investigation on this subject in order to present the advantages and disadvantages of such an application.

Nanofluid's Properties Consideration

The base fluid's transport properties are influenced by the addition of the solid nanoparticles, which in one hand enhances the fluid's thermal conductivity but also directly contribute to enhance its liquid density and viscosity. Proper consideration must be made regarding the addition of the solid nanoparticles as those properties might directly influence the overall thermal management and pumping analysis. Some models have been developed to better describe the influence of the addition of nanoparticles on pure substances and the gain on the liquid thermal conductivity that might represent (Koo and Kleinstreuer, 2004) as usually the Maxwell model is applied on this case as

$$k_n = \frac{k_p + 2\ k_l + 2\left(k_p - k_l\right)\ f}{k_p + 2\ k_l - \left(k_p - k_l\right)\ f}\, k_l \,. \qquad \text{W/m°C} \qquad [1]$$

Equation [1] represents the effective thermal conductivity of a homogeneous suspension. Since the liquid thermal conductivity is affected by the addition of a nanoparticle in the substance, proper consideration and evaluation of the solid particles in a liquid must be taken according to the two-phase theory (Carey, 2008). Thus, the nanofluid density is then calculated as

$$\frac{1}{\rho_n} = \left(\frac{f}{\rho_p} + \frac{1-f}{\rho_l} \right) \qquad \text{kg/m}^3 \qquad [2]$$

and the liquid dynamic viscosity is then calculated as (Xuan and Roetzel, 2000):

$$\mu_n = \mu_l \frac{1}{(1-f)^{2.5}}. \qquad \text{Pa.s} \qquad [3]$$

The modification of the transport properties indicated in Eqs. [1] to [3] should be included in any analysis to correctly address their influence on the system's thermal performance.

Equipment Design and Operation

A specific design for a surveillance equipment (defense application) has been conceived to operate in hostile environments where the ambient temperatures can range from +5 to +50 °C and humidity levels up to 95%. In this case, a single-phase thermal control loop has been designed with potential use of nanofluid, which would present a forced circulation using a pump to move the working fluid throughout the architecture of the circuit to remove heat from the electronic components, rejecting this heat to the environment by a fan cooling system. A schematic of such arrangement is presented by Fig. 1.

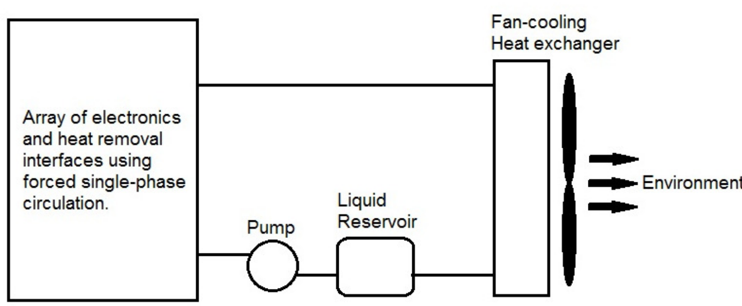

Figure 1: Schematics of the thermal control system arrangement.

Details of the surveillance equipment and its architecture are considered proprietary information and cannot be disclosed at this time. For the sake of the necessary information to perform the adequate analysis, the system's characteristics are:

- Heat rejection of up to 50 kW to the environment;
- Working fluid circulation in a hydraulic diameter of 11 mm through 45 m of tubes, disposed in parallel lines connected by manifolds to the main transport lines, pump, reservoir and fan cooling;
- Maximum required temperature difference between the inlet and outlet of the fan cooling system is 15 °C;
- The working fluid is circulated by using a pump and an electronic control sets the pump and fan speeds in order to adjust their operation, according to the working fluid's set point temperature.

As the base fluid, water has been selected for this first approach. This working fluid has been selected for a proof of concept for the system's design, as well as its availability and its perfect compatibility with the selected nanoparticle, which is copper oxide (CuO). For this investigation, the CuO nanoparticles present an average diameter of 29 nm and purity of 99.8%. The nanoparticles concentration (*f*) shall vary from 3.5% to 20% (by mass of the base fluid) to verify their effect on the overall thermal performance of the system. For every value of *f* the pump is able to promote the nanofluid's circulation as the loop's overall pressure drop was lower than the pumping capacity selected. Since the nanoparticles are dissolved in the base fluid, they will both present the same flow rate for a given concentration, as presented on the results of Fig. 3a.

Results and Discussion

Considering the operation conditions that the thermal management system of the surveillance equipment needs to face, several analytical simulations were conducted in order to check the temperature differences across the system, pressure drop throughout the loop and heat rejection capability. For this investigation, energy, mass and momentum equations were derived and implemented in this analytical simulation, which can be addressed from any standard thermal/hydraulic model. For this model, it has been considered all the parallel flow across the electronics components and power supplies. More details regarding the model cannot be disclosed at this time due to the sensitive technology involved on this project.

For the calculations, the system was considered to be operating at 4 different temperatures for the working fluid, measured at the fan cooling outlet (25, 35, 45 and 55 °C), and 5 conditions of the nanofluid, being pure water and its mixture with CuO nanoparticles at the concentrations of *f*=3.5%, *f*=5.0%, *f*=10% and *f*=20%. For the presented results, the environment temperature at which heat was being dissipated was set at 15 °C. The results obtained from the simulations were used as guidance for the investigation of the potentiality of using the nanofluid for a better performance of the entire thermal management system.

Figures 2a and 2b present some results for the pressure drop and heat transfer coefficients, respectively, on a comparison between the use of pure water and the addition of copper nanoparticles at different concentrations (*f*), by mass percentage of working fluid in the system. It is clear that as the concentration increases, the pressure drop also increases up to 32% for *f*=20% as more solid nanoparticles are present in the system and the pump needs to overcome the extra resistance as the transport properties are changed with the addition of the nanoparticles. However, the increase of the heat transfer coefficients is also clear and can represent a gain around 12% for the same *f*=20% which cannot be neglected.

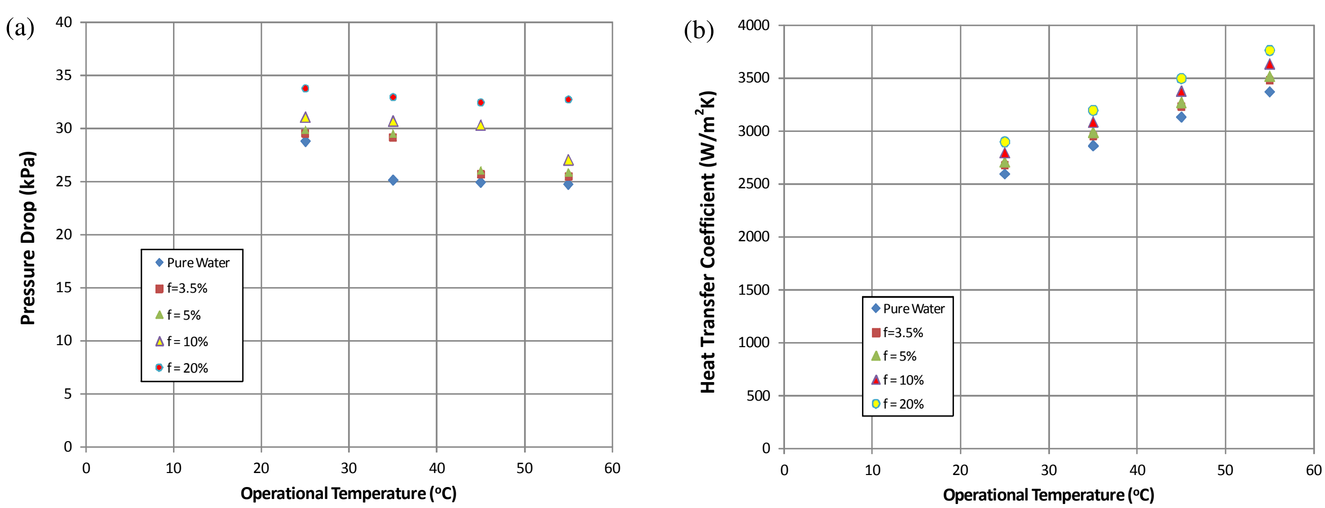

Figure 2: Analytical results for (a) pressure drop and (b) heat transfer coefficient.

It can be observed from Fig. 2(a) that the increase of the nanoparticle concentration directly affects the pressure drop as expected. Since the addition of the solid nanoparticle contributes to the increase of the liquid's viscosity and density, those properties directly influence the pressure drop calculation. The difference between the pressure drop when using water and its related nanofluid with *f*=20% can be 32% higher when operating at 55 °C, which can compromise the pump's operation if not well designed. However, when analyzing the heat transfer coefficient, it is clear that the nanofluid enhances this parameter as the concentration increases. For *f*=20%, the heat transfer coefficient can be 12% higher than when operating with pure water at 55 °C. Such an improvement on this parameter can guide the design towards the use of nanofluids as it represents that the working fluid will present the required temperature difference between the fan cooling inlet and outlet without the need of using an enhanced heat transfer surface with a special internal geometry for the tubes that could represent additional costs to the project. As of today, regular off-the-shelve pumps can operate with the nanofluid with up to *f*=20% without representing additional costs to the project or the need of a pump with a special design.

Other parameters can also be analyzed from this simulation, which are presented by Fig. 3 related to the (a) volumetric flow rate and (b) the pump required power needed to circulate the fluid in the loop. As presented by Fig. 3(a), the volumetric flow rate required decreases with the increase of the fraction of solid nanoparticles, as this parameter is directly connected to the transport properties. Upon increasing the fraction of solid nanoparticles, the working fluid becomes more dense and viscous, reducing the amount of fluid circulating in the loop.

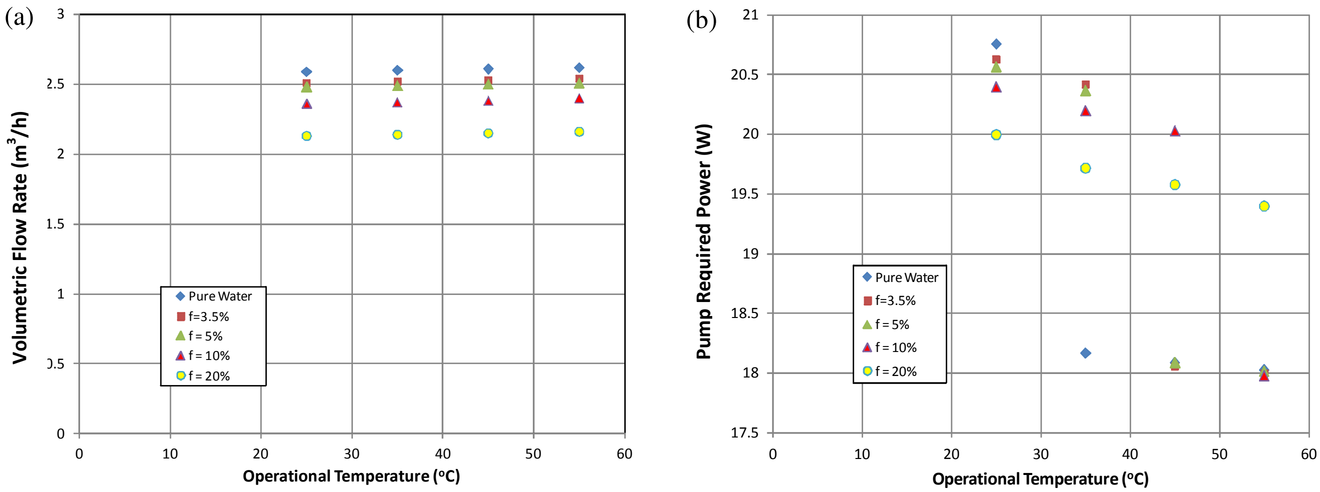

Figure 3: Analytical results for (a) volumetric flow rate and (b) pump required power.

Due to the particularities of the loop's architecture (i.e. manifolds' fittings, etc), the required pumping power varies as presented by Fig. 3(b), indicating that at 55 °C higher pumping power will be required for *f*=20% but at 25 °C higher pumping power would be required upon operating with water. Even though the difference between the lower and higher required pumping power is around 3 W, it represents variations up to 12%. However, such a parameter is not the major issue as the selected pumps for this project can support such variations without major problems and the gain observed on the heat transfer coefficient justify the use of more powerful pumps, since the gain on reducing the size of the thermal management system is a powerful argument for its application.

Conclusions

Even though the use of nanofluids can represent a gain on the heat transfer coefficient and thus a new option for the design of heat management devices, it must be carefully considered regarding the pumping requirements. For the present investigation, the use of nanofluids is going on the direction of reducing the size of the thermal management system conceived to remove the heat from the electronic components of the surveillance equipment. In general, the main conclusions that can be derived from this investigation are:

1. Higher heat transfer coefficients can be reached with the increase of the fraction of solid nanoparticles concentration, representing an enhancement of up to 12% for *f*=20% at 55 °C when compared with the operation with water;
2. The pressure drop also increases as the concentration of nanoparticles increases, which could compromise the pump operation;
3. Lower volumetric flow rates are observed for higher concentration of nanoparticles, as this factor contributes to increase the working fluid's viscosity and density;
4. Even with the use of solid nanoparticles, the required pumping power does not represent to be the major issue on the project, as this requirement can be easily addressed as the calculated values are rather low;

5. The overall analysis indicates that the application of the nanofluid with higher concentrations can be used, as the major parameter for this analysis is the heat transfer coefficient, which is reducing the size of the thermal management device of the electronics components.

When considering that the thermal management system is operating at higher capacities, while keeping the working fluid's temperature differences between the fan cooling inlet and outlet within the required parameters, the use of a nanofluid presents to be an important innovative approach for this project. This is directly resulting in more gains than loses for the overall thermal system analysis and should remain as the most indicated solution for this application.

Nomenclature

f	Fraction of solid nanoparticles (% by mass)
k	Thermal conductivity (W/m°C)
ρ	Density (kg/m^2)
μ	Dynamic viscosity (Pa.s)

Subscripts

n	Nanofluid
p	Solid particle
l	Liquid

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