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Finned tube performance evaluation with nanofluids and conventional heat transfer fluids

Roy Strandberg, Debendra K. Das*

Department of Mechanical Engineering, University of Alaska Fairbanks, P.O. Box 755905, Fairbanks, AK 99775-5905, USA

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ABSTRACT

The performance of hydronic finned-tube heating units with nanofluids is compared to their performance with a conventional heat transfer fluid comprised of 60% ethylene glycol and 40% water, by mass (60% EG) using a mathematical model. The nanofluids modeled are comprised of either CuO or Al_2O_3 nanoparticles dispersed in the 60% EG solution. The finned tube configuration modeled is similar to that commonly found in building heating systems. The model employs correlations for nanoparticle thermophysical properties and heat transfer that have been previously documented in the literature. The analyses indicate that finned tube heating performance is enhanced by employing nanofluids as a heat transfer medium. The model predicts an 11.6% increase in finned-tube heating output under certain conditions with the 4% Al_2O_3/60% EG nanofluid and an 8.7% increase with the 4% CuO/60% EG nanofluid compared to heating output with the base fluid. The model predicts that pumping power required for a given heating output with a given finned tube geometry is reduced with both the Al_2O_3/60% EG and the CuO/60% EG nanofluids compared to the base fluid. The finned tube with 4% Al_2O_3/60% EG has the lowest liquid pumping power at a given heating output of all the fluids modeled.

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1. Introduction

Heat transfer fluids that are enhanced with extremely small particles (less than 100 nm in their characteristic dimension, often called "nanoparticles") in dispersion, are often referred to as "nanofluids". These fluids have been shown in studies by multiple authors to exhibit superior thermal conductivity [4] to that predicted by conventional correlations developed for fluids enhanced with micrometer-sized particles. Other studies have focused on developing correlations to predict the Nusselt number of internal flows for nanofluids. For example, the work of Li and Xuan [8], Xuan and Li [18], suggests that Nusselt numbers for nanofluids are superior to those of the base fluid under certain flow conditions (for instance, when directly compared at equal Reynolds numbers). The higher Nusselt numbers, combined with higher thermal conductivity yields superior convective heat transfer compared to conventional heat transfer fluids coefficients in internal flow situations. The dispersion of the nanoparticles into fluids also results in higher viscosity that is related to particle mean diameter, concentration and temperature. Under certain flow conditions (for constant average liquid velocity, for instance), this can result in increased pumping losses. The higher viscosity also contributes to a reduction in Reynolds number, which decreases the Nusselt number when compared to conventional fluids under constant velocity conditions. These factors must be weighed against each other in evaluating the suitability of nanofluids for use in heat transfer applications.

Finned tube radiators are often used to provide comfort heating in perimeter zones within occupied spaces of buildings. These finned tubes are comprised of a copper tube or steel pipe with thin, rectangular fins mechanically crimped onto the outside diameter at regular intervals. Heat transfer fluid is pumped through the copper tubing while room air is drawn over the fins by natural convection, thereby accomplishing heat transfer between the hot heating fluid and the cooler room air. The application of nanofluids in these finned tube radiators may result in several potential benefits including increased heating output for equal liquid flow. These performance impacts, in turn, may be translated into a reduction in total required heat transfer area. This trait can used to reduce the materials of construction needed to achieve a given rate of the heating output. Superior heat transfer properties of nanofluids may also result in lower liquid flow rate for a given rate of heat transfer, yielding a reduction in the liquid pumping power consumed compared to the base fluid.

The objective of this work is to characterize the performance of finned tube radiators with CuO/60% EG and Al_2O_3/60% EG nanofluids

* Corresponding author. Tel.: +1 907 474 6094; fax: +1 907 474 6141.
E-mail address: dkdas@alaska.edu (D.K. Das).

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at different volumetric concentrations, and to compare the finned tube radiators' performance to that with the 60% EG base fluid. In cold regions of the world such as Alaska, 60% EG is employed as a heat transfer fluid because of its extreme freeze resistance. Heating output for a given finned tube geometry is characterized using the nanofluids and the base fluid. Also characterized are frictional pressure loss, pumping power and heat transfer area associated with a given heating output using the nanofluids and the base fluid.

2. Analysis

The methodology employed to determine finned-tube heating capacity was based on several previously developed correlations for thermophysical properties. Selected correlations for properties of the air and the 60% ethylene glycol/water solution were based on curve-fits generated from published property data.

2.1. Heat transfer fluid thermophysical properties

In this analysis, liquid filled finned-tube heating capacity is compared for a variety of different heat transfer fluids. These include 60% ethylene glycol/40% water solution (heretofore referred to as 60% EG) and nanofluids comprised of a 60% EG base fluid with CuO or Al_2O_3 nanoparticles uniformly dispersed in volumetric concentrations of 4% or less. Thermophysical property data for the 60% EG were taken from ASHRAE Fundamentals [1]. Thermophysical properties for air are taken from Bejan [2].

For all curve-fits applied to 60% EG property data (Eqs. (2), (8) and (11) below) and corresponding data for air (Eqs. (1), (7), and (10)), $R^2 > 0.99$. These correlations are applicable for 60% EG between 273 K < T < 370 K, and for air between 173 K < T < 333 K. These temperatures are comparable to those seen in facility heating systems.

2.1.1. Density

For density of air, a polynomial curve-fit was applied to the property data, with $R^2 > 0.99$. The equation for the fitted polynomial is

$$\rho_{air} = 2.3548 \times 10^{-5} \cdot T^2 - 1.7928 \times 10^{-2} \cdot T + 4.4289 \quad (1)$$

where ρ_{air} is in kg/m^3. For density of the 60% EG, a polynomial curve-fit was applied to the ASHRAE data. The equation for the fitted curve is

$$\rho_{bf} = -0.002475 \cdot T^2 + 0.9998 \cdot T + 1002.5023 \quad (2)$$

where ρ_{bf} is in kg/m^3. Pak and Cho [10] developed a relationship for the effective density of nanofluids. This is used for both types of nanofluids considered. It is stated as:

$$\rho_{nf} = \phi\rho_s + (1-\phi)\rho_{bf} \quad (3)$$

2.1.2. Specific heat

For specific heat of air, a constant value of 1006 J/kg K is used. For specific heat (J/kg K) of the 60% EG, a linear curve-fit was applied to the ASHRAE data. The equation for the fitted curve is:

$$c_{p,bf} = 4.248 \cdot T + 1882.4 \quad (4)$$

Buongiorno [3] has developed a relation for effective specific heat of nanofluids. Buongiorno's correlation is employed for evaluating the specific heat of CuO nanofluids. It is stated as:

$$c_{p,nf} = \frac{\phi\rho_s c_{p,s} + (1-\phi)\rho_{bf}c_{p,bf}}{\rho_{nf}} \quad (5)$$

From experiments on Al_2O_3 nanoparticles in 60% EG, Vajjha and Das [16] developed a specific heat correlation. It is stated as

$$\frac{c_{p,nf}}{c_{p,bf}} = \frac{\left((AT) + B\left(\frac{c_{p,s}}{c_{p,bf}}\right)\right)}{(C+\phi)} \quad (6)$$

where $A = 0.000891$, $B = 0.5179$ and $C = 0.4250$ and 315 K < T < 363 K; $0.01 < \phi < 0.1$. Also, c_p is in kJ/(kg K).

2.1.3. Viscosity

For viscosity of air (in Pa s), a linear curve-fit was applied to the property data, with $R^2 > 0.99$. The equation for the fitted line is

$$\mu_{air} = 5.2638 \times 10^{-8} \cdot T + 2.6384 \times 10^{-6} \quad (7)$$

For viscosity of the 60% EG (in mPa s), a curve-fit based on Andrade's equation presented by Reid et al. [11] was applied to the ASHRAE data. The equation of this curve-fit is

$$\ln(\mu_{bf}) = 3135.6\left(\frac{1}{T}\right) - 8.9367 \quad (8)$$

This correlation applies for 273 K < T < 360 K.Vajjha [14], developed the following correlations based on experimental data of Namburu et al. [9] for computing the viscosity (in mPa s) of nanofluids comprised of CuO and Al_2O_3 nanoparticles dispersed in 60% EG base fluid

$$\frac{\mu_{nf}}{\mu_{bf}} = Ae^{B \cdot \phi} \quad (9)$$

where $A = 0.9830$ and $B = 12.9590$ for Al_2O_3 with ϕ up to 10% $(0 < \phi < 0.10)$ $A = 0.9197$ and $B = 22.8539$ for CuO with ϕ up to 6% $(0 < \phi < 0.06)$.

This viscosity correlation was developed for 273 K < T < 360 K.

2.1.4. Thermal conductivity

For thermal conductivity of air (W/m K), a linear curve-fit was applied to the property data, with $R^2 > 0.99$. The equation for the fitted line is

$$k_{air} = 7.5576 \times 10^{-5} \cdot T + 3.1203 \times 10^{-3} \quad (10)$$

For thermal conductivity of the 60% EG, a polynomial curve-fit was applied to the ASHRAE data. The equation of this curve-fit is

$$k_{bf} = -3.196 \times 10^{-6} \cdot T^2 + 2.512 \times 10^{-3} \cdot T - 0.10541 \quad (11)$$

From experiments on CuO and Al_2O_3 nanoparticles dispersed in 60% EG, Vajjha and Das [15] developed a thermal conductivity correlation based on an improvement of the Koo–Kleinstreuer [7] model.

$$k_{nf} = \left(\frac{k_s + 2k_{bf} - 2\phi(k_{bf} - k_s)}{k_s + 2k_{bf} + \phi(k_{bf} - k_s)}\right)k_{bf} + 5 \times 10^4 \beta\phi\rho_{bf}c_{p,bf}\sqrt{\frac{\kappa T}{\rho_s d_p}}f(T,\phi) \quad (12a)$$

where
$$f(T,\phi) = (2.8217 \times 10^{-2}\phi + 3.917 \times 10^{-3})(T/T_o) - (3.0669 \times 10^{-2}\phi + 3.91123 \times 10^{-3}).$$

For nanofluids comprised of Al_2O_3 nanoparticles,

$$\beta = 8.4407(100\phi)^{-1.07304} \quad (12b)$$

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