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Development of new correlations for the Nusselt number and the friction factor under turbulent flow of nanofluids in flat tubes

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ABSTRACT

A three-dimensional turbulent flow and heat transfer of two different nanofluids, containing aluminum oxide (Al_2O_3) and copper oxide (CuO) nanoparticles, dispersed in ethylene glycol and water mixture (EG/W) in the flat tubes of an automotive radiator have been numerically studied to evaluate their performance. Computations have been carried out for nanoparticles volumetric concentrations up to 6% and over a Reynolds number range typically encountered in automobile radiators. Appropriate correlations for density, viscosity, specific heat and thermal conductivity of nanofluids as a function of particle volume concentration and temperature, developed from experiments have been used in this study. Numerical results have been first validated for the flow of single phase liquids, such as water and EG/W by comparing the computed values of Nusselt number and friction factor with those given by accurate correlations available in the literature. Inside the flat tube continuous reductions in the local heat transfer coefficient and wall shear stress are observed around the periphery of the flat tube, starting from the mid-point of the flat-wall and proceeding to the center of the curved wall. For the same Reynolds number, computations with nanofluids show an increase of friction factor and heat transfer coefficient with an increase in the particle volume concentration. The study reveals that under the basis of equal pumping power, Al_2O_3 and CuO nanofluids up to 3% and 2% particle volumetric concentrations respectively provide higher heat transfer coefficients than that of the base fluid. From the present study, several new correlations to determine the Nusselt number and friction factor for the nanofluids flowing in the flat tubes of a radiator have been proposed for the entrance as well as the fully developed regions.

1. Introduction

The material need for automobiles can be diminished by reducing the size of radiators, which also present the added benefit of fuel efficiency due to the reduction in weight. Additionally, due to the steady rise in the cost of the fuel of automobiles, there is an increasing demand on improving their overall efficiency. To accomplish this, over the years, many new fin designs have evolved resulting in newer and compact designs to improve radiators. Kays and London [1] present comprehensive collection of data on a variety of compact heat exchanger geometries. When it comes to the heat transfer fluid consideration, they have not been improved. Common coolants are: water, mixtures of ethylene glycol or propylene glycol mixed with water. Advent of nanofluids, which are stable suspensions of nanoscale particles (<100 nm), promises to improve the performance of radiators by improving the coolant heat transfer capability.

A significant amount of literature is available on the performance of single phase fluids in radiators from the publications of the society of automotive engineers. However, literatures on nanofluids performance in radiators are quite limited. Therefore, the purpose of the present paper is to conduct a comprehensive analysis of nanofluids flow in the flat tube of an automotive radiator and compare their performance with single phase fluids.

Some literatures that compared the performance of commonly used single-phase heat transfer fluids in radiators are reviewed below. Gollin and Bjork [2] compared the heat transfer and hydraulic performance of coolants, such as pure water, pure propylene glycol, 50/50 and 70/30 volume mixtures of both EG/W and propylene glycol/water (PG/W) for five automobile radiators through wind tunnel experiments. Based on their experiments, they concluded that in terms of heat transfer and lowest pressure drop, the most effective of coolants was pure water, followed by 50/50 EG/W, 50/50 PG/W, 70/30 EG/W, 70/30 PG/W and finally pure PG. JuGer and Crook [3] compared the heat transfer performance of 50/50 EG/W and 50/50 PG/W mixtures in two different geometries of truck radiator. They observed that heat transfer

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Nomenclature

A	cross-sectional area, m^2
C_f	Fanning skin friction coefficient
C_p	specific heat, J/kg K
d_p	nanoparticle diameter, m
D_h	hydraulic diameter of the tube, $D_h = 4A/P_m$, m
h	heat transfer coefficient, $h = q''/(T_w - T_b)$, W/m^2 K
k	thermal conductivity, W/m K
L	length of the tube, m
Nu	Nusselt number, $Nu = (hD_h/k)$
N_X, N_Y, N_Z	number of nodes in X, Y, Z directions
P	pressure, Pa
P_m	perimeter, m
Pr	Prandtl number, $Pr = (\mu\ C_p/k)$
q''	heat flux, W/m^2
Re	Reynolds number, $Re = (\rho\ VD_h/\mu)$
T	temperature, K
T_o	reference temperature, 273 K
$\dot{W}$	pumping power, W
V	velocity, m/s
Z_H	hydrodynamic entry length, m
Z_T	thermal entry length, m
Z	axial distance from the inlet, m

Greek symbols

ϕ	particle volumetric concentration,%
ρ	density, kg/m^3
μ	viscosity, mPa s
κ	Boltzmann constant, 1.381×10^{-23} J/K
τ	shear stress, Pa

Subscripts

avg	peripheral average
b	bulk
p	nanoparticle
nf	nanofluid
bf	base fluid
w	wall
Z	local axial position
ZA	average on respective walls

Superscript

-	average over the tube length

performance of 50/50 EG/W mixture is better than that of 50/50 PG/W mixture under the same operating conditions. This seems reasonable as EG/W has better thermophysical properties than PG/W. Cozzone [4] compared the heat transfer performance of EG/W with PG/W mixtures of various proportions ranging from 30% to 70% in a 3.8 L V6 gasoline engine. His study revealed that PG/W and EG/W mixtures showed almost equal heat transfer performance. He attributed this phenomenon to an improved heat transfer characteristics of the PG based coolants over the EG based coolants under nucleate boiling conditions, which may be occurring in the engine block.

The conventional approach of increasing the heat rejection rate of automobile radiators by the use of external fin geometries and various tube shapes have already been widely explored. Poor thermal properties of traditional heat transfer fluids have prompted the present day researchers to look for new technologies that will improve the fluid's heat transfer characteristics, thereby improving the cooling efficiency of automobile radiators. As explained earlier, one such technology that shows the potential to improve the traditional heat transfer fluids is the concept of nanofluids. Nanofluids are the stable dispersions of nanometer-sized particles in conventional base fluids [5,6]. With the suspension of high thermal conductivity metals or metallic oxide nanoparticles in these traditional coolants, the thermal conductivity of the resulting mixture is increased [7–9]. Up until now two most widely studied nanoparticles are the Al_2O_3 and CuO. Minkowycz et al. [10] summarize the latest developments in nanofluids research up to 2013 in a treatise addressing different aspects through a systematic exposition in ten chapters.

Only a limited number of publications have appeared thus far on the application of nanofluids in automotive radiators. Vasu et al. [11] theoretically analyzed using the effectiveness-number of transfer unit (ε-NTU) method for the application of the Al_2O_3 nanoparticles dispersed in water as a coolant in flat tube plain fin compact heat exchanger. Their analysis showed a substantial increase in the cooling capacity of the Al_2O_3 nanofluid compared to the base fluid. They also observed an increase in the pressure drop of nanofluid over the base fluid. Leong et al. [12] performed similar analysis using copper nanoparticles of up to 2% particle volumetric concentration suspended in ethylene glycol base fluid. They observed a heat transfer enhancement of 3.8% over the base fluid at the Reynolds number of 6000 and 5000 for air and coolant respectively, for a 2% particle volumetric concentration of nanofluid. Vajjha et al. [13] numerically studied a three-dimensional laminar flow and heat transfer performance of Al_2O_3 and CuO nanoparticles dispersed in ethylene glycol/water mixture circulating through the flat tubes of a Chrysler minivan radiator. For a 10% Al_2O_3 and a 6% CuO nanofluids, their analysis showed an increase in the average heat transfer coefficient of about 94% and 89% respectively over the base fluid, at a Reynolds number of 2000. They also observed that for the same amount of heat transfer, the Al_2O_3 nanofluid of 10% concentration and the CuO nanofluid of 6% concentration showed a reduction in pumping power of about 82% and 77% respectively when compared to the base fluid. Peyghambarzadeh et al. [14] experimentally investigated the heat transfer performance of the Al_2O_3 nanoparticles dispersed in different base fluids including pure water, pure EG and mixtures of EG and water (5, 10, 20 vol.% EG) as coolants in an automobile radiator. Their experiments showed that the heat transfer characteristics of the nanofluids were strong functions of particle volume concentration and the flow conditions. At optimal conditions, they obtained heat transfer enhancement of 40% when compared to the base fluids. Chavan and Pise [15] conducted an experimental study on the Al_2O_3 nanoparticles suspended in pure water in an automobile radiator. With the addition of 1% volume concentration of nanoparticles to the base fluid water, they presented a heat transfer enhancement of 40–45% over the base fluid. Hussein et al. [16] studied numerically the friction factor and heat transfer enhancement of a TiO_2 nanofluid flow in turbulent regime through circular, elliptical and flat shaped tubes. They observed that with the addition of the titanium oxide nanoparticles in water, the friction factor and the heat transfer coefficient increased. On the other hand, they reported that with an increase in the Reynolds number, the friction factor decreased and the heat transfer coefficient increased. They concluded that the flat tube gave the lowest friction factor and a higher heat transfer coefficient when compared to the elliptical