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Experimental and numerical investigations of nanofluids performance in a compact minichannel plate heat exchanger

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Three nanofluids comprising of aluminum oxide, copper oxide and silicon dioxide nanoparticles in ethylene glycol and water mixture have been studied theoretically to compare their performance in a compact minichannel plate heat exchanger (PHE). The study shows that for a dilute particle volumetric concentration of 1%, all the nanofluids show improvements in their performance over the base fluid. Comparisons have been made on the basis of three important parameters; equal mass flow rate, equal heat transfer rate and equal pumping power in the PHE. For each of these cases, all three nanofluids exhibit increase in convective heat transfer coefficient, reduction in the volumetric flow rate and reduction in the pumping power requirement for the same amount of heat transfer in the PHE. On the cold fluid side of the heat exchanger, a coolant, HFE-7000, has been studied, which has the potential for application in extremely low temperatures, but has not been investigated widely in the literature. Experimental data measured from a minichannel PHE in a test loop using water as the base fluid have validated the test apparatus with excellent agreement of predicted heat transfer rate and the overall heat transfer coefficient with the experimental values. From experiments on a 0.5% aluminum oxide nanofluid, preliminary correlations for the Nusselt number and the friction factor for nanofluid flow in a PHE has been derived. This apparatus will be useful to test different kinds of nanofluids to ultimately determine the effects of parameters such as: volumetric concentration, particle size and base fluid properties on thermal and fluid dynamic performance of nanofluids in compact heat exchangers.

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1. Introduction

Nanofluids are stable suspensions of nanometer-sized particles, less than 100 nm, in conventional base fluids such as water, ethylene glycol, propylene glycol, oil and other liquids. Addition of high thermal conductivity metallic nanoparticles such as copper or aluminum increases the thermal conductivity of such colloidal solutions, thus enhancing their overall heat transfer capability. Starting with the initial research of Choi and Eastman [1] in 1995, the past decade and half has witnessed an abundant amount of experimental as well as numerical studies to explore the advantages of nanofluids as a heat transfer medium over the conventional liquids. Das et al. [2] have compiled a comprehensive volume on various aspects of research on the science and technology of nanofluids in their book covering the progress up to 2006. A new book edited by Minkowycz et al. [3] presents ten chapters contributed by experts in the field summarizing the latest developments of nanoparticle heat transfer and fluid flow up to 2013. At present nanofluids research occurs worldwide, showing a general conclusion that nanofluids can be a superior heat transfer fluid. This objective can be achieved provided the design conditions of nanofluids flowing in heat exchanges are carefully optimized by parametric runs to take advantage of the proper combination of the thermophysical properties of nanofluids. In this paper we have addressed how the effect of these properties yields superior performance.

Since nanofluids are a new class of engineered fluids, a great deal of research efforts has been devoted thus far to determining their thermophysical properties accurately, because they are essential to determine the convective heat transfer and the pumping power. However, until now, a limited amount of research has been presented on the theoretical analysis and actual testing of nanofluids in heat exchangers to compare their thermal and fluid dynamic performances with conventional fluids. To augment this lack of data, we have begun experimental and theoretical investigations of nanofluids and base fluids in plate heat exchangers (PHEs). The approach presented in this paper can be easily adapted to any type of compact heat exchanger.

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Nomenclature

A, B, C	dimensionless coefficients
A_f	fluid flow area per channel, m^2
A_p	projected area per plate, m^2
A_t	surface area on one fluid side of PHE, m^2
b	channel spacing, m
C	heat capacity rate, W/K
c_p	specific heat, J/kg K
D_e	equivalent diameter, m
d_p	particle diameter, m
f	fanning friction coefficient
h	convective heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
L	plate length, m
LMTD	log mean temperature difference, K
$\dot{m}$	mass flow rate, kg/s
N	no. of channels
NTU	number of transfer units
Nu	Nusselt number, $Nu = hd/k$
Pr	Prandtl number, $Pr = (\mu C_p)/k$
Q	heat transfer rate, W
R^2	coefficient of determination
Re	Reynolds number, $Re = (\rho V d)/\mu$
t	thickness of plate, m
T	temperature, K
T_0	reference temperature, 273 K
U	overall heat transfer coefficient, W/m^2 K
V	mean velocity, m/s
$\dot{V}$	volumetric flow rate, m^3/s
W	plate width, m
$\dot{W}$	pumping power, W

Greek letters

β_{phe}	chevron angle, °
ΔP	differential pressure loss, Pa
μ	coefficient of dynamic viscosity, kg/m s
ϕ	particle volumetric concentration
ϕ_{phe}	enlargement factor
ρ	density, kg/m^3
κ	Boltzmann constant, 1.381×10^{-23} J/K
ε	heat exchanger effectiveness

Subscripts

0	properties at reference temperature, 273 K
avg	average
bf	base fluid
c	cold fluid stream
f	fluid
h	hot fluid stream
i	inlet
nf	nanofluid
o	outlet
p	particle

The motivation for this research comes from exploring the application of nanofluids as the coolant in the active thermal control (ATC) loop to dissipate heat from NASA's future spacecrafts. The ATC loop presented by Ungar and Erickson [4] is shown in Fig. 1. The amount of heat generated in the crew module is about 2.5 kW which has to be dissipated through a compact liquid to liquid heat exchanger [4,5]. In the present study, we have examined a compact PHE of this thermal rating due to its ease of availability to compare nanofluids performance. According to the classification described by Kandlikar et al. [6], this is a minichannel heat exchanger, because the smallest channel dimension necessary to meet this classification is 3 mm and our heat exchanger has a channel dimension of 2 mm. Compact heat exchangers have heat transfer area to volume ratio starting around 700 m^2/m^3 as described by Shah [7]. This PHE has a compactness factor of about 1000 m^2/m^3, placing it well into the realm of compact heat exchangers. Although this paper covers a PHE, from the knowledge of the described methodology it will be a straightforward extension to substitute in the experiment or analysis, characteristics of other types of compact heat exchangers and evaluate their performance under nanofluids flows. The test loop described in this paper under the Experimental Study section can be adapted to testing different types of compact heat exchangers, microchannel devices, heat sinks and cold plates, which find wide applications in the thermal management. Due to the continuous miniaturization of electronic devices and micro electromechanical systems, the heat density has increased significantly over the years. Therefore, the investigation on nanofluids, which are shown in this paper to have superior thermal performance than the corresponding base fluids shows, be capable of removing high heat flux in compact heat exchangers. The information presented here should be beneficial in optimizing thermal management systems. For NASA, the reduction in size, weight and pumping power for heat exchangers would translate to substantial cost savings, since it costs about $12,000 [8] to lift 1 lb. of payload into orbit.

Plate heat exchangers have been widely studied for single phase fluids and subsequently have found applications in two-phase vapor–liquid flows occurring in condensers and evaporators. A recent comprehensive book by Wang et al. [9] covers all aspects of PHE applicable for base fluids, but not for nanofluids. The research on nanofluids flow in plate heat exchanger is quite limited and we cite some of them here. Mare et al. [10] experimentally studied two nanofluids, Al_2O_3 and carbon nanotubes dispersion in pure water under laminar flow conditions. They measured a 42% and 50% improvement in heat transfer coefficient for Al_2O_3 and carbon nanotube suspensions respectively, when compared with pure water. They described a parameter to compare the heat transfer gain versus the pumping power loss due to the use of nanofluids and reported a gain of 22% and 150% for Al_2O_3 and carbon nanotube respectively, while comparing thermal–hydraulic performance with pure water. Jokar and O'Halloran [11] conducted computational fluid dynamic (CFD) analysis on Al_2O_3-water nanofluid with volumetric concentrations of 1–4% in the laminar flow regime. Their results showed that as the nanofluids volumetric concentration increased the total heat transfer in the PHE decreased slightly. They attributed this unusual behavior to the complex flow regimes in the three dimensional geometries of PHEs. Many researchers have shown that the heat transfer rate increases with an increase in the concentration in simple flow geometries as in circular pipes. Another reason for their under prediction of the heat transfer rate may be due to the thermal conductivity correlation they used in their computation. Their thermal conductivity plot shows a very low enhancement of about 2% at a fixed temperature even for an appreciable particle volumetric concentration of 4%. This unusually low value of thermal conductivity enhancement could be easily nullified by the standard l error in a CFD computational.

Pantzali et al. [12] performed experimental investigation of a 4% copper oxide (CuO) suspension in water in a PHE transferring heat up to 3.5 kW. Their experimental data showed a nearly similar

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