Available online at www.sciencedirect.com
SCIENCE DIRECT®
Applied Thermal Engineering 26 (2006) 2209–2218
APPLIED THERMAL ENGINEERING
www.elsevier.com/locate/apthermeng

Heat transfer enhancement with the use of nanofluids in radial flow cooling systems considering temperature-dependent properties

Samy Joseph Palm, Gilles Roy *, Cong Tam Nguyen

Faculty of Engineering, Université de Moncton, Moncton, NB, Canada E1A 3E9

Received 3 June 2005; accepted 28 March 2006
Available online 22 May 2006

Abstract

Heat transfer enhancement capabilities of coolants with suspended metallic nanoparticles inside typical radial flow cooling systems are numerically investigated in this paper. The laminar forced convection flow of these nanofluids between two coaxial and parallel disks with central axial injection has been considered using temperature dependent nanofluid properties. Results clearly indicate that considerable heat transfer benefits are possible with the use of these fluid/solid particle mixtures. For example, a Water/Al_2O_3 nanofluid with a volume fraction of nanoparticles as low as 4% can produce a 25% increase in the average wall heat transfer coefficient when compared to the base fluid alone (i.e., water). Furthermore, results show that considerable differences are found when using constant property nanofluids (temperature independent) versus nanofluids with temperature dependent properties. The use of temperature-dependent properties make for greater heat transfer predictions with corresponding decreases in wall shear stresses when compared to predictions using constant properties. With an increase in wall heat flux, it was found that the average heat transfer coefficient increases whilst the wall shear stress decreases for cases using temperature-dependent nanofluid properties.

Keywords: Nanofluids; Nanoparticles; Heat transfer; Laminar flow; Confined radial flow

1. Introduction

Engineers and scientists have been quite active over the past few decades in the search of novel ways to increase heat removal performances of various cooling devices. For example, recent technological advances in manufacturing have led to the miniaturisation of many components in numerous applications. These include many electronic devices, such as microprocessors, where continually increasing power densities are requiring more innovative techniques of heat dissipation. One common heat removal technique is the use of radial flow cooling systems (i.e., impinging jet systems with or without confinement). Researchers have investigated the use of such cooling systems for various cutting-edge applications, including electronic equipment cooling (see for example [1,2]). Albeit now somewhat dated, Downs and James [3] made a good overview of impinging jet heat transfer. Projects have included the analysis of flow behaviour and heat transfer characteristics of impinging jet systems with or without confinement, as well as fixed or rotating disks systems for various practical applications (see for example, [4,5]). Coolants used in such applications include air (or other gases), water, oil and other more recently developed cooling fluids such as FC-77 liquid. Considerable efforts have been made in studying the effects of various geometrical configurations on heat transfer characteristics of radial flow cooling systems. Although advances have been made, major improvements in heat transfer capabilities using traditional fluids have been limited due to the somewhat lacklustre heat transfer properties of traditional coolants.

Aware of the limited heat transfer capabilities of these traditional coolants, engineers and researchers have long

* Corresponding author. Tel.: +1 506 858 4323/4300; fax: +1 506 858 4082.
E-mail address: roy@umoncton.ca (G. Roy).

1359-4311/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.applthermaleng.2006.03.014

Nomenclature

a	gap separating disks (m)
C_p	specific heat of the fluid (J/kg K)
D_h	hydraulic diameter (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity of the fluid (W/m K)
L	inlet tube length (m)
P	pressure (Pa)
Pr	Prandtl number, $Pr = C_p\mu/k$ (–)
q''_w	surface heat flux (W/m^2)
Q	volumetric flow rate (m^3/s)
Re	inlet Reynolds number, $Re = 2Q/\pi D_h \nu$ (–)
R_i	inlet orifice radius (m)
R_{ext}	disk outside radius (m)
r	radial coordinate (m)
$\bar{r}$	$\bar{r} = r/D_h$ (–)
T	temperature (K)
z	axial coordinate (M)
$\bar{z}$	$\bar{z} = z/D_h$ (–)
V	velocity vector (m/s)
V_r	radial velocity component (m/s)
V_z	axial velocity component (m/s)
V_0	inlet fluid axial velocity (m/s)

Greek letters

α	thermal diffusivity (m^2/s)
β	R_{ext}/D_h
η	a/D_h
ϕ	volume concentration of particles
μ	fluid absolute viscosity (kg/m s)
ν	fluid kinematic viscosity (m^2/s)
θ	tangential coordinate (rad)
ρ	fluid density (kg/m^3)

Subscripts

amb	refers to ambient condition
bf	base fluid
i	refers to a direction in space
nf	nanofluid
p	refers to particles
r, θ, z	refer to the directions in space
0	refers to the inlet condition

considered using small metallic particles in suspension in common fluids. It is well known that metals have much higher thermal conductivities than those of typical coolants. Therefore, it seems quite reasonable to assume that the resulting mixture will have enhanced heat removal capabilities, even with a small particle percentage. Published work on various mixtures using millimetre or micrometer sizes particles have started to appeared over a hundred years ago, for example [6–9]. Other contributions on the performances of mixtures can be found for gas-solid particle mixtures [10–15] and liquid–solid particle mixtures [16,17]. Although considerable heat transfer enhancements were found with the use of two-phase mixtures, adverse effects such as channel clogging, increased pressure losses and pipeline erosion have generally halted practical application developments.

Advances in manufacturing technologies have made the production of particles in the nanometre scale possible (i.e., 10 nm $\leqslant$ particle diameter $\leqslant$ 100 nm). Over the past few years, researchers have looked into the possibility of using this new class of nanometer-sized particles (hence the term "nanoparticles") for heat transfer enhancement capabilities of traditional coolants [18]. Initial research into these resulting mixtures, named "nanofluids", seem to indicate that the problems encountered with the inclusion of larger particles are considerably reduced with the use of nanoparticles [19,20]. Results have shown that oxide nanoparticles (for example Al_2O_3 and CuO) have excellent dispersion properties in water, oil and ethylene glycol and form stable suspensions that even seem to behave more like single-phase fluids than two phase mixtures [21]. Furthermore, these initial results have shown that the thermal properties of nanofluids appear to be considerably higher than those of the base fluid alone. For example, increases of roughly 20% in the effective thermal conductivity were found experimentally for as little as 1–5% in particle volume fraction of the mixture [20–22]. It is for these reasons that it is believed that nanofluids have the potential of becoming interesting alternatives for leading-edge high efficiency cooling requirements.

As one will easily notice, the majority of the available literature on the topic thus far, albeit very limited, is focused on their physical and thermal properties. Recent relevant reviews of work on nanofluids may be found in [23,24]. A few papers can be found on the determination of the effective thermal conductivities [18–22,25–28] and/or effective nanofluid viscosities of various nanofluids [19,22,29]. It is also noticed that, for a same type of nanofluid, results presented by different authors exhibit considerable dispersion. Possible reasons for this could be, amongst others, particle size/shape effects, temperature effects, particle-clustering, etc. These are all effects that are currently not very well understood and initial papers on their influences are just beginning to appear [19,30–33]. In the particular case of temperature effects on effective nanofluid properties, initial results presented in these