THERMAL CONDUCTIVITY AND RHEOLOGY OF CNT NANOFLUIDS STABILIZED WITH GUM ARABIC

BY

RASHMI G WALVEKAR

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Kulliyyah of Engineering
International Islamic University
Malaysia

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ABSTRACT

A nanofluid is a suspension of nano sized particles in a base fluid. It is very much essential to know more about stability and thermal characteristics of such a nanofluid for their further use in practical applications. In the present work, Multiwalled Carbon Nanotubes (CNT) are dispersed in water. CNT dispersed in water are highly unstable and they sediment rapidly due to the Vander Waals force of attraction. Thus, to overcome this limitation Gum Arabic (GA) was added which acted as a potential dispersant. Experimental work consisting of stability studies under the effects of CNT concentration (0.01-0.1 wt%), GA concentration (0.25-5.0 wt%) and sonication time (1-24hr), respectively have been carried out. Stability was measured using UV-Vis spectrophotometer. Thermal conductivity, density and rheology of the most stable suspensions were measured as a function of temperature (25-60°C) and CNT concentration. pH of the nanofluid suspensions have also been measured. Further, convective heat transfer experiments were conducted in a laminar flow heat exchanger for CNT concentration of 0.01wt%. GA concentration and sonication time was found to play important role in dispersion of CNTs in water. Nanofluids are found to be stable at 4.0hr sonication time and the optimum GA concentration was found to be between 1.0-2.5 wt% for the range of the CNT concentration studied. Thermal conductivity was observed to be strongly dependent on temperature and CNT concentration. The enhancement in thermal conductivity was from 4.03-125.6% and 37.4-287.5% as the temperatures varied from 25-60 °C, for 0.01wt% and 0.1wt% of CNT, respectively. CNT nanofluids showed slightly shear thinning behavior at low shear rates (<400s^{-1}) and clear Newtonian behavior at high shear rates (400-1000s^{-1}) and temperature. Further, viscosity was also found to be a function of CNT and GA concentration. No significant change in viscosity and density was observed in the presence of GA and CNT and the CNT nanofluid was found to be more stable in pH range between 4.5-5.5. The results on laminar flow using CNT nanofluids show increase in heat transfer coefficient up to 68-138%, which implies nanofluids as promising fluids for heat transfer application. In this study, a new model for thermal conductivity was proposed to explain the possible enhancement, by taking temperature, viscosity of the fluid, Brownian motion, shape and aspect ratio of CNTs apart from other properties of fluid and particles. The proposed model was found to be in good agreement within <10% deviation with experimental data on all CNT nanofluids available in the literature. However, the discrepancy increase as the CNT concentration increased beyond 0.06 volume fraction, which could be primary limitation of the model. Numerical simulations were carried out for 0.01, 0.04 and 0.1wt%, CNT using FLUENT by single phase approach. Numerical results are validated with the theoretical models and experimental results. The numerical results were found to be in good agreement (± 10% error) with the experimental results at low CNT concentration while the deviation increased to 16% with particle concentration. In summary, CNT nanofluids are found to be more suitable for heat transfer applications in many industries due to their enhanced thermal conductivity property. This work provides large information on behavior of CNT nanofluids. The major contributions of this work includes production of stable CNT nanofluid using gum Arabic, various parameters affecting stability of the nanofluid and theoretical model for thermal conductivity.

خلاصة البحث

تعتبر محاليل النانو nanofluids من المعلقات لدقائق متناهية الصغر في سائل. ومن المهم ان نحيط علما باستقراريتها وتصرفها تحت درجات حرارية متباينة للحصول على معلومات بهدف الاستفادة العملية منها. في هذا البحث درست انابيب نانو من الكاربون CNT متعددة الجدران معلقة في وسط مائي. هذه المحاليل تعتبر غير مستقرة بسب تواجد قوة "فان در والز" ومن اجل التغلب على هذه الحالة تم اضافة "الصمغ العربي GA " والذي يعمل على تشتيت هذه القوة. درست محاليل حاوية على CNT بتراكيز (0.01-0.1 wt%), وبوجود GA بتراكيز (0.25-5.0 wt%) ولفترة زمنية تراوحت بين (1-24hr), باستخدام UV-Vis spectrophotometer. تم دراسة المواصفات الحرارية والكثافة والريولوجية بدرجات حرارية تراوحت بين (25-60°C) وتراكيز محاليل CNT والدالة الحامضية pH للمحاليل .اضافة الى ذلك اجريت تجارب على تصرفاتها الحرارية باستخدام مبادلات حرارية لمحاليل CNT والحاوية على GA .0.01wt% وتبين أن تأثيرعامل الزمن مهم جدا على استقرارية المعلقات المائية. تبين ايضا ان المعلقات بقت صامده لفترة 4.0 ساعات من sonication time وان افضل التراكيز من الصمغ العربي GA كانت تتراوح بين 1.0-2.5 wt% للتراكيز من CNT التي تم دراستها. أما الموصلية الحرارية فوجد بآنها تعتمد على درجات الحرارة وتراكيز CNT . إن تضخم "enhancement " الموصلية الحرارية الحاصل كان بين 4.03-125.6% and 37.4-287.5% وضمن درجات حرارية 25-60 °C للتراكيز 0.01wt% and 0.1wt% منCNT , على التوالي. كما تبين بأن محاليل النانو nanofluids تتأثر قليلا shear thinning بمعدلات بسيطة (<$400s^{-1}$) وتتصرف كمحاليل Newtonian عند معدلات سحب (400-$1000s^{-1}$). و وجد بأن اللزوجة ذاتها تتأثر بتراكيز كل من CNT and GA. لم يلاحظ اي تغير باللزوجة والكثافة بوجود GA وCNT كما وجد بان محاليل النانو nanofluids اظهرت استقرارا بدالات حامضية تراوحت بين.4.5-5.5. أظهرت النتائج ايضا بان استخدام محاليل النانو الحاوية علىCNT زيادة في في معامل نقل الحرارة بمقدار تراوح بين 68-138% وهذا يدل على ان محاليل النانو مرشحة في استخدامات التبادل الحراري. نقدم في هذه الدراسة نموذجا للنقل الحراري يوضح امكانية تحسينها بدراسة درجة حرارة واللزوجة للسائل والحركة البراونية ونسب CNT إضافة الى المتغيرات الاخرى للسائل و الدقائق. يبن النموذج المعروض توافق بحدود درجة تباين < 10%> على جميع محاليل النانو الحاوية على CNT والواردة في الادبيات. بدأت الاختلافات تظهر بزيادة تراكيز CNT اكثر من 0.06 (نسب حجمية) والذي يحدد امكانية استخدام النموذج المطروح. أجريت تجارب محاكات على محاليل حاوية على تراكيز 0.01, 0.04 and 0.1wt%, من CNT باستخدام FLUENT وبطور واحد. اظهرت النتائج تطابقا مع الموديلات النظرية وفق النتائج التي تم الحصول عليها وضمن تباين لا يتعدى (± 10% error) عندما يكون تركيز CNT قليلا، بينما زاد التباين الى 16% بزيادة تركيز الدقائق العالقة. وفي الختام ،ان ابرز ما يقدمه بحثنا هذا هو : إمكانية استخدام محاليل النانو nanofluids كوسط للتبادل الحراري في صناعات متعددة نظرا لما تمتلكه من صفات جيدة. كما ويقدم البحث معلومات قيمة عن تصرفات محاليل النانو nanofluids ، وسلوكياتها، وطرق تحظيرها، و استقراريتها ـ إضافة الى تقديمنا موديلا للتبادل الحراري.

APPROVAL PAGE

The thesis of Rashmi Walvekar has been approved by the following:

Ahmad Faris Ismail
Supervisor

Faridah Yusof
Co-supervisor

Mohammed Saedi Jami
Internal Examiner

Mirghani Ishaq Ahmed
Internal Examiner

Wan Ramli Wan Daud
External Examiner

Abdi Omar Shuriye
Chairman

DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Rashmi Walvekar

Signature ____________________ Date _____________________

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This research is dedicated to my parents and family for their endless support and affection

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Symbols		Units
A_i	Internal heat transfer flow area	m^2
A	Flow area	m^2
A_o	External heat transfer flow area	m^2
A_m	Mean heat transfer flow area	m^2
$B_{2,x}$	Depolarization factor along x axis	-
$C_{p,h}$	Specific heat of hot fluid	J/kgK
$C_{p,c}$	Specific heat of cold fluid	J/kgK
$C_{p,p}$	Specific heat of the particle	J/kgK
$Cp_{,f}$	Specific heat of the fluid	J/kgK
$C_{p,eff}$	Effective specific heat	J/kgK
D_p	Diffusivity of the particle	m^2/s
D	Pipe diameter	m
D_o	Outer diameter of outer pipe	m
D_i	Inner diameter of outer pipe	m
d_o	Outer diameter of inner tube	m
d_p	Diameter of the particle	m
d_i	Inner diameter of inner tube	m
G_z	Gratz number	-
G_r	Grashoff number	-
g	Acceleration due to gravity	m/s^2
h	Heat transfer coefficient	W/m^2K
J_x	Heat current vector	W
k_{pe}	Equivalent particle thermal conductivity	W/mK
k_p	Particle thermal conductivity	W/mK
k_f	Fluid thermal conductivity	W/mK
k_{cl}	Cluster thermal conductivity	W/mK
$k_{c,x}$	Effective dielectric constant along x axis	W/mK
k_i	Thermal conductivity of the interface	W/mK
k_B	Boltzmann constant	m^2kg/s^2K
L	Length of the pipe	m
l_p	Length of the particle	m
$\dot{m}_h$	Mass flow rate of hot fluid	kg/s
m	Mass	kg
$\dot{m}_c$	Mass flow rate of cold fluid	kg/s
N	Number of Brownian particles	-
Nu	Nusselt number	-
n_f	Number of fluid molecules per unit volume	$1/m^3$
n_p	Number of particles per unit volume	$1/m^3$
n_s	Shape factor	-
P_r	Prandtl number	-
P_e	Peclet number	-

$\dot{Q}_c$	Heat transfer rate of cold fluid	W
$\dot{Q}_h$	Heat transfer rate of hot fluid	W
$\dot{Q}_{avg}$	Average heat transfer rate	W
q	Over all heat transfer rate	W
q_f	Heat transfer rate due to fluid	W
q_p	Heat transfer rate due to particle	W
R_e	Reynold number	-
r_p	Radius of the particle	m
r_f	Radius of the fluid molecule	m
r_{cl}	Radius of the cluster	m
S_o	Annulus flow area	m^2
S_f	Surface area of the fluid molecules paer unit volume	m^2
S_p	Surface area of the particles per unit volume	m^2
t	Time	s
T	Temperature	K
u,v,w	Velocity components	m/s
V	Volume of the system	m^3
μ_{f}	Fluid viscosity	kg/ms
$\mu_{\mathrm{ef}}\mathrm{f}$	Effective viscosity	kg/ms
ρ_f	Density of the fluid	kg/m^3
ρ_p	Density of the particle	kg/m^3
ρ_{eff}	Effective density	kg/m^3
γ	Shear rate	s^{-1}
ζ	Drag on the particles	Pas
τ	Increment time	s
ϕ_{max}	Maximum volume fraction	-
ϕ	Volume fraction of the particle	-
ϕ_{eff}	Effective volume fraction of the particles	-
ϕ_{cl}	Volume fraction of the cluster	-
Ψ	Sphericity	-

LIST OF ABBREVATIONS

Ag	Silver
Ag_2Al	Silver alumina
Al	Aluminum
Al_2Cu	Aluminum copper
Al_2O_3	Aluminum oxide
ANL	Argonne national laboratory
Au	Gold
BmimPF6	1-butyl-3-methylimidazolium hexafluorophosphate
C	Carbon
CFD	Computational Fluid dynamics
CMC	Carboxy methyl cellulose
CNF	Carbon nanofibres
CNT	Carbon nanotube
CTAB	Cetyltrimethyl ammonium bromide
Cu	Copper
CuO	Cuprous oxide
DWCNT	Double walled carbon nanotubes
EG	Ethylene glycol
F-CNT	Functionalized carbon nanotubes
Fe	Iron
Fe_2O_3	Ferrous oxide
GA	Gum arabic

HCl	Hydrochloric acid
HEC	Hydroxy ethyl cellulose
MWCNT	Multiwalled carbon nanotubes
MEMS	Micro electromechanical systems
NaDDBS	Sodium dodecyl benzen sulfonate
Ni	Nickle
SDBS	Sodium dodecyl benzene sulfonate
SDS	Sodium dodecyl sulphate
SEM	Scanning electron microscopy
SiC	Siliconcarbide
SWCNT	Single walled carbon nanotubes
TEM	Transmission electron microscopy
TiO_2	Titanium oxide
VTF	Vogel-Tammann-Fulcher

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

In today's world downsizing has become a new trend in the world of science and technology. Micro electromechanical systems (MEMS) technology and nanotechnology are rapidly emerging and developing as the new revolution in miniaturization, which is strongly interdisciplinary. For example, miniature heat exchangers have numerous attributes, including high thermal effectiveness, high heat transfer surface-to volume ratio, small size, low weight, low fluid inventory and design flexibility.

Nanoparticles are now easily produced using modern material technology with sizes less than 100nm. These nanoparticles have different mechanical, electrical, thermal and optical properties compared to their parent material. The stable suspension of these nanoparticles in conventional base fluids is known as nanofluid, which was first coined by Choi (1995) at the Argonne National Laboratory (ANL), Chicago. Since the development of the concept of nanofluids, many scientists and researchers all over the world have made scientific breakthrough in developing unexpected thermal properties enhancement and also studied and proposed new mechanisms behind enhanced thermal properties of nanofluids.

Great interest has recently been developed in the area of nanostructured carbon materials. Carbon nanomaterials are gaining commercial importance with interest growing rapidly over the decade or so since the discovery of buckminsterfullerene, carbon nanotubes, and carbon nanofibers (Dresselhaus et al., 2001). Carbon nanotubes

(CNT) and carbon nanofibers (CNFs) are among the most eminent materials in nanotechnology. The most eye-catching features of these structures are their unique electronic, mechanical, optical, thermal and chemical characteristics, which open new applications.

Ultrahigh performance cooling is one of the most important needs in today's cooling industries. Low thermal conductivity of conventional base fluids (for example, water 0.6 W/mK and ethylene glycol 0.2W/mK) is a primary limitation in developing energy efficient heat transfer fluids. The conventional way to enhance heat transfer rate is by increasing the surface area of cooling devices and the flow velocity. Another way is to disperse solid particles in conventional heat transfer fluids. Due to increasing need for efficient cooling technologies in many industries, a new approach to enhance heat transfer is necessary. Thus, a small amount of nanoparticles uniformly suspended in conventional base fluids can dramatically enhance the heat transfer characteristics of these base fluids. Cooling is one of the top technical challenges facing high tech industries such as micro-electronics, transportation, manufacturing, metrology and defense with heat load increasing 25kW or heat flux exceeding 2000W/cm^2. In the transportation industry, cooling is a crucial issue due to the trend towards higher engine power and exhaust gas regulation or hybrid vehicles, inevitably leads to larger radiators and increased frontal areas, resulting in additional aerodynamic drag and higher fuel consumption. Thus, nanofluids can offer a great potential in developing high performance, cost effective, compact liquid cooling systems.

Thermal conductivity of heat transfer fluids plays a vital role in the development of energy efficient heat transfer fluids. Conventional base fluids such as oils, water and ethylene glycol have inherently poor thermal conductivities, orders of magnitude smaller than solid particles. Metals in solid form at room temperature have orders of magnitude higher thermal conductivities than liquids as shown in Table 1.1.

Table 1.1
Thermal conductivity of various materials (Das et al., 2008)

Material	Material	Thermal conductivity (W/m K)
Metallic solids	Silver	429
	Copper	401
	Aluminum	237
Non-metallic solids	Diamond	3300
	Carbon nanotubes	3000
	Silicon	148
	Alumina (Al_2O_3)	40
Metallic Liquids	Sodium at 644 K	72.3
Non-metallic liquids	Water	0.613
	Ethylene glycol	0.253
	Engine oil	0.145

Nanofluids produced are expected to give the following benefits (Patel, 2007).

i. Nanofluids can be made stable and homogeneous with the use of nominal stabilizing agent combined with other techniques such as ultrasonic vibrations and high speed homogenisation.

ii. Very less sedimentation occurs because of higher stability of nanofluids. Also the particles are always in motion, which assures no fouling.

iii. Due to the small size and less momentum of particles, there will be practically no erosion of the components.

iv. Very minor increase in pressure drop occurs resulting from the friction between fluid and particles. However, these nanoparticles may sit in the surface irregularities thereby making them smoother which reduce the friction between fluid and the wall. The resultant effect may be even minor reduction in pressure drop.