HEAT TRANSFER AUGMENTATION OF WATER BASED TIO_2 AND SIO_2 NANOFLUIDS IN A TUBE WITH TWISTED TAPE

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ABSTRACT

Nanofluids have gained extensive attention due to their role in improving the efficiency of thermal systems. Conflicting statements are made in the literature regarding heat transfer enhancements with nanofluids. The objective of the present work is to evaluate heat transfer coefficients through experiments for flow of water, TiO_2 and SiO_2 nanofluids under similar operating conditions to determine the characteristics under which heat transfer enhancements with nanofluids can be obtained in comparison with water. The properties of TiO_2 and SiO_2 nanofluids are required at different concentrations, temperature and particle size. Hence, a generalized equation for the evaluation of viscosity and thermal conductivity of nanofluids is developed with the available experimental data in the literature. A test rig is fabricated with the facility to heat the liquid by wrapping with two nichrome heaters on the tube with an option to insert a twisted tape. Experiments are undertaken to determine heat transfer coefficients and friction factor with water based TiO_2 and SiO_2 nanofluids at 30 ^{o}C in the turbulent range of Reynolds number for flow in a tube and with twisted tape. The experimental data indicates enhancement with concentration up to 1 % and 3 % with TiO_2 and SiO_2 nanofluids respectively for flow in a tube. A maximum of 33 % enhancement at 3 % and 26 % at 1 % volume concentration over water are observed with SiO_2 and TiO_2 nanofluids respectively for flow in a tube. A further increase in concentration from these values, reduced the heat transfer coefficients. It has been determined that the heat transfer coefficient decrease when the viscosity to thermal conductivity enhancement ratio is greater than 5 which is confirmed with the experimental values of TiO_2 and SiO_2 nanofluids. It can be stated that enhancement in heat transfer depends on concentration and operating temperature of the nanofluid. An increase in heat transfer coefficient and friction factor with a decrease in twist ratio for water and nanofluids is observed from experiments. The experimental results indicated a maximum heat transfer coefficient of 81.1 % with TiO_2 nanofluid at 1 % concentration with insert of twist ratio 5 when compared to flow of water in a tube. However, at the same twist ratio, a maximum enhancement of 94.1 % in heat transfer coefficient at 3 % concentration with SiO_2 nanofluid is observed. The nanofluid friction factor with twist ratio of 5 is greater than twice the value obtained for flow of water in a tube at volume concentration higher than 2.5 %. The use of nanofluid is justified from thermo-hydraulic considerations with the estimation of 'advantage ratio'. For the case of plain tubes, it is preferable to have the flow of TiO_2 and SiO_2 nanofluids at 1 % and 3 % concentrations, respectively. Meanwhile for nanofluid flow with twisted tape, it is recommended to use the twist ratio of 15. The use of TiO_2 nanofluids with twisted tape is suggested for volume concentrations higher than 1 %. However, the use of SiO_2 nanofluids with twisted tape is not recommended due to lower advantage ratio compared to nanofluid flow in plain tubes. The experimental data of Nusselt number obtained with twisted tape is validated with the results of the theoretical model developed. The characteristics of nanofluid flow and heat transfer are also determined. The flow of nanofluid over a twisted tape is observed to enhance heat transfer.

ABSTRAK

Bendalir nano telah mula mendapat perhatian yang meluas kerana kemampuannya untuk meningkatkan kecekapan sistem haba. Terdapat perbezaan kenyataan dalam penerbitan lepas mengenai penambahbaikan pemindahan haba menggunakan bendalir nano. Objektif kajian ini adalah untuk mengenalpasti pekali pemindahan haba melalui kaedah eksperimen bagi aliran air, bendalir nano TiO_2 dan SiO_2 pada keadaan operasi yang sama untuk menentukan ciri-ciri di mana bendalir nano dapat bertindak sebagai bendalir pemindahan haba yang baik dibandingkan dengan air. Sifat-sifat bendalir nano TiO_2 dan SiO_2 diperlukan pada kepekatan, suhu dan saiz zarah yang berbeza. Persamaan-persamaan telah dibangunkan bagi menganggar sifat-sifat kekonduksian haba dan pekali kelikatan bendalir nano menggunakan data yang sudah diterbitkan. Peralatan ujikaji telah direkabentuk bagi tujuan memanaskan bendalir menggunakan dua pemanas nikrom yang dibalut pada tiub dan juga kemudahan untuk memasukkan pita berpintal. Ujikaji dijalankan bagi menentukan pekali pemindahan haba dan geseran untuk bendalir nano TiO_2 dan SiO_2 berasaskan air pada 30 ^{o}C bagi nombor Reynolds aliran gelora untuk aliran dalam tiub bersama pita berpintal. Data eksperimen menunjukkan peningkatan pada kepekatan sehingga 1 % (TiO_2) dan 3 % (SiO_2) untuk aliran dalam tiub. Bendalir nano telah menghasilkan pemindahan haba maksimum sebanyak 33 % pada kepekatan 3 % untuk SiO_2, manakala TiO_2 menghasilkan 26 % peningkatan maksimum pada kepekatan 1 % dibandingkan dengan air untuk aliran dalam tiub. Dengan peningkatan kepekatan yang lebih tinggi daripada nilai-nilai tersebut telah mengurangkan pekali pemindahan haba. Ianya telah ditentukan bahawa pekali pemindahan haba menurun apabila nisbah peningkatan kelikatan kepada peningkatan kekonduksian haba lebih besar daripada 5 seperti yang disahkan secara eksperimen bagi bendalir nano TiO_2 dan SiO_2. Oleh itu, peningkatan pemindahan haba adalah bergantung kepada kepekatan dan suhu operasi bendalir nano. Pekali pemindahan haba dan geseran meningkat dengan penurunan nisbah pintalan untuk aliran air dan bendalir nano telah diperhatikan melalui eksperimen. Keputusan eksperimen menunjukkan pekali pemindahan haba maksimum sebanyak 81.1 % menggunakan bendalir nano TiO_2 pada kepekatan 1 % dan nisbah pintalan 5 berbanding dengan aliran air dalam tiub. Walau bagaimanapun pada nisbah pintalan yang sama, peningkatan maksimum sebanyak 94.1 % bagi kepekatan 3 % menggunakan bendalir nano SiO_2. Pekali geseran bendalir nano pada nisbah pintalan 5 adalah dua kali ganda lebih tinggi daripada aliran air dalam tiub untuk kepekatan lebih besar daripada 2.5 %. Kewajaran penggunaan bendalir nano melalui pertimbangan termo-hidraulik dapat ditentukan menggunakan ‘nisbah kelebihan’. Bagi aliran dalam tiub, dicadangkan menggunakan bendalir nano TiO_2 pada kepekatan 1 %, manakala bendalir nano SiO_2 pada kepekatan 3 %. Sementara itu, bagi aliran bendalir nano dengan pita berpintal adalah disyorkan menggunakan nisbah pintalan 15. Penggunaan bendalir nano TiO_2 bersama pita berpintal dicadangkan pada kepekatan yang lebih tinggi daripada 1 %. Walau bagaimanapun, penggunaan bendalir nano SiO_2 bersama pita berpintal tidak digalakkan kerana nisbah kelebihan yang lebih rendah berbanding dengan aliran bendalir nano dalam tiub. Data eksperimen nombor Nusselt untuk aliran bersama pita berpintal telah disahkan melalui keputusan model berangka yang telah dibangunkan. Ciri-ciri aliran bendalir nano dan pemindahan haba juga ditentukan. Aliran bendalir nano bersama pita berpintal diperhatikan dapat meningkatkan kadar pemindahan haba.

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

CHAPTER 2 LITERATURE REVIEW

CHAPTER 3 METHODOLOGY

CHAPTER 4 RESULTS AND DISCUSSION

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A	Constant
A^+	Constant in van Driest expression
α	Nanoparticle Biot number
α_{nf}	Thermal diffusivity of nanofluid
α_p	Thermal diffusivity of particle
α_w	Thermal diffusivity of water
B	Constant
β	Ratio of nanolayer thickness to particle radius
β_1	Constant
C	Centreline
C_{nf}	Specific heat of nanofluid
C_p	Specific heat of particle
C_{pbf}	Specific heat of base fluid
C_{RM}	Random motion velocity of a nanoparticle
C_w	Specific heat of water
C_1	Constant
d_{bf}	Equivalent diameter of a base fluid molecule
$d_{\max}$	Maximum particle size
d_p	Particle diameter
d_p^*	Upper limit of nanoparticle diameter
D	Tube inner diameter

δ	Thickness of strip
ΔP	Pressure drop
ΔV	Volume of distilled water for dilution
ε_H	Eddy diffusivity for heat
ε_m	Eddy diffusivity for momentum
η	Intrinsic viscosity
f	Darcy friction factor,
f_{SL}	Friction factor of Smithberg and Landis
f_B	Blasius friction factor
f_{nf}	Friction factor of nanofluid
γ	Ratio of thermal conductivity of the layer to particle
h	Heat transfer coefficient
H	Inter particle spacing
H	Helical pitch of the twisted tape for 180° rotation
K_{eff}	Effective thermal conductivity
K_{bf}	Thermal conductivity of the base fluid
K_w	Thermal conductivity of water
K	Thermal conductivity
K_p	Thermal conductivity of the particle
K_{neff}	Net effective thermal conductivity
K_B	Boltzmann constant
K_i	Thermal conductivity of the interfacial shell
K_m	Matrix conductivity

K_{pe}	Equivalent thermal conductivity of particle
K_r	Thermal conductivity of nanofluid to water ratio, (K_{nf} / K_w)
k	Coefficient in eddy diffusivity equation of van Driest
L	Tube length
L_h	Hydrodynamic entry length
l_{bf}	Mean free path of base fluid
M	Molecular weight of the base fluid
m	Constant
m_p	Mass of particle
m_w	Mass of water
m_0	Ambient temperature during heating
m_1	Ambient temperature during cooling
m_2	Rate of background temperature drift
m_3	Slope of temperature rise to logarithm of temperature
μ_r	Ratio of nanofluid to water viscosity
μ_{nf}	Absolute viscosity of nanofluid
μ_{bf}	Absolute viscosity of base fluid
μ_w	Absolute viscosity of water
N	Avogadro number
n	Empirical shape factor
Nu	Nusselt number
Nu_{nf}	Nusselt number of nanofluid
ω	Weight concentration in percent

ω_1	Constant in equation (2.21)
Pr	Prandtl number
$\Pr_{bf}$	Prandtl number of base fluid
$\Pr_{nf}$	Prandtl number of nanofluid
$\Pr_{w}$	Prandtl number of water
Pe_d	Peclet number of particle
ϕ	Volume concentration in percent
φ	Volume concentration in fraction
φ_m	Maximum volume concentration in fraction
ψ	Sphericity
π_1	Ratio of nanofluid temperature
π_2	Ratio of nanoparticle diameter
π_3	Ratio of nanoparticle to water thermal diffusivity
π_4	Volume concentration in percent / ϕ
Q	heat input
q	Heat flux
R	radius of the tube
R_b	Interfacial thermal resistance between nanoparticle and fluid
Re	Reynolds number
Re_B	Brownian-Reynolds number
Re_p	Reynolds number of particle
R^+	Dimensionless radius, $\left(\frac{\mathrm{R}}{\nu}\sqrt{\frac{\tau_W}{\rho}}\right)$

ρ_{bf0}	Density of base fluid at 20^{o}C
ρ_{bf}	Density of base fluid
ρ_p	Density of particle
ρ_w	Density of water
T	Temperature
T_b	Bulk temperature
T_e	Exit temperature
T_{fr}	Freezing point of base liquid
T_i	Inlet temperature
$T_{\max}$	Maximum temperature
T_{nf}	Temperature of nanofluid
T_{nf}^{*}	Upper limit of temperature
T_0	Reference temperature
T_s	Surface temperature
T_w	Temperature of water
T^{+}	non-dimensional temperature, $\left(\frac{T_W - T}{T_W - T_C}\right)$
t	Time
t_h	Heating time
t_1	Thickness of the shell
τ	Shear stress
θ / θ_2	Fraction of the liquid volume travels with particle
u	velocity
u^{+}	non-dimensional velocity, (u/u*)

u^*	shear velocity, $\left(\sqrt{\frac{\tau_W}{\rho}}\right)$, (m/s)
υ	Kinematic viscosity
υ_{nf}	Kinematic viscosity of nanofluid
V_1	Initial volume
V_2	Final volume
V	Input voltage
$\bar{V}$	Average velocity
y	Distance measured normal to the wall
y^+	Dimensionless distance measured normal to the wall, $\left(\frac{yu^*}{\nu}\right)$
ξ	Prandtl exponent
w	water
W	wall

LIST OF ABBREVIATIONS

AD	Average deviation
Al_2O_3	Aluminium oxide
AR	Advantage ratio
CAD	Computer-aided design
CFD	Computational fluid dynamics
CNT	Carbon nanotubes
CTAB	Cetyl Trimethyl Ammonium Bromide
Cu	pure Copper
CuO	Copper oxide
EC	Electrical conductivity
EDL	Electrical double layer
EG	Ethylene glycol
EO	Engine oil
exp	Experiment
Fe_3O_4	Iron oxide
HEG	Hydrogen exfoliated grapheme
hp	Horsepower
htc	Heat transfer coefficient
ID	Inner diameter
lpm	Liter per minute
MD	Maximum deviation
MWCNT	Multi walled carbon nanotubes
OD	Outer diameter
PER	Property enhancement ratio

PT	Plain tube
SD	Standard deviation
SDBS	Sodium Dodecyl Benzene Sulphonate
SiC	Silicon carbide
SiO_2	Silicon dioxide
TEG	Thermal exfoliated graphene
TEM	Transmission electron microscopy
TiO_2	Titanium oxide
TNT	Titanate Nanotube
TT	Twisted tape
PO	Pump oil
ZnO	Zinc oxide
ZrO_2	Zirconium dioxide

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

The determination of forced convection heat transfer coefficient for flow of liquids such as water, ethylene glycol and oils have gained importance due to their diverse applications in the transfer of thermal energy (Ahuja, 1975). The design of heat exchanger thermal systems with single phase fluids for the estimation of heat transfer coefficient is undertaken for a wide range of parameters and operating conditions. The performance of these systems with conventional fluids in transferring heat, however, has reached the limit. Enhancements in heat transfer coefficient lead to miniaturization of thermal equipment which has become prominent. Various methods for heat transfer enhancements have been developed over the years, either, to accommodate high heat fluxes in a limited space or to minimize the size of the equipment. The augmentation of heat transfer can be achieved through active and passive methods as suggested by Ahuja (1975) and Bergles (1985). Active heat transfer enhancement is due to the application of external energy on the fluid whereas passive enhancement of heat transfer by introducing treated surfaces, extended surfaces, displaced enhancement devices, swirl flow devices, coiled tubes, surface tension devices, and additives in the conventional liquid or combination of various passive techniques (compound enhancement). The use of passive method proved successful in achieving better heat transfer augmentation without any substantial increase in pressure drop (Bergles, 1985).

One such passive method of achieving heat transfer enhancement using additives has been initiated with the dispersion of micron sized solid particles in a base fluid such as water (Choi and Tran, 1991). Since the thermal conductivity of a metal is significantly higher than the liquid, the effective thermal conductivity is enhanced, leading to greater heat transfer coefficient. These high performance fluids can contribute to the evolution of space-saving yet cost effective thermal equipments with higher competitive demand in the global market. The addition of micron sized particles in liquids occasionally contributes to the problems of clogging, fouling and erosion of pipe lines. This therefore results in high pumping power requirements. Further, agglomeration and resettlement of particles posed a severe maintenance problem. Studies for developing new thermal fluids for enhanced heat transfer capabilities have been investigated by dispersing high thermal conducing ultra-fine particles of nanometer size in base liquids. The nanoparticles are able to suspend uniformly in the base fluids to improve the effective thermal conductivity of the solution. These fluids are known as nanofluids, which promised good rheological properties, better stability and higher thermal conductivity. The nanometer sized particles proved effective in achieving heat transfer augmentation without any significant increase in pumping power requirements and other practical problems (Darzi et al., 2012; Kayhani et al., 2012 and Pang et al., 2015).

The implementation of insert in a tube is another passive heat transfer augmentation such as swirl flow with twisted tapes, longitudinal inserts, wire coils, ribs and dimples. The methods have been reported by Bergles (1988) for a wide range of Reynolds and Prandtl numbers. The most common insert devices frequently utilized in engineering applications are twisted tapes and wire coils. These inserts are employed because of their ease of manufacture, simple installation and low cost (Pan et al., 2013). According to Wang and Sundén (2002), wire coil inserts show overall heat transfer performance better than twisted tape inserts if pressure drop is considered as one of the key parameters. Twisted tape inserts however, give higher heat transfer enhancement rather than wire coil inserts. Webb and Kim (2005) investigated that the twisted tape insert is the best insert device. Manglik and Bergles (1993a, b) stated that the twisted tape causes the flow to swirl, providing longer path lengths and residence time. In addition, the tape is also able to induce more turbulent characteristic to the flow and prevent the formation of the boundary layer. Tape inserts are commonly used for heat transfer enhancements in several applications in processes involving heat recovery, solar heating, air conditioning and refrigeration systems, and chemical reactors.

Enhancement in the heat transfer rate is achieved with tape inserts, thus reducing the heat exchanger size, however, with increase in pressure drop. The pressure drop is higher due to the resistance that is caused by the additional tape surface area when compared to flow in plain tubes.

The use of nanometer sized particles for use as heat transfer fluid was started by a research group at the Argonne National Laboratory. Masuda et al. (1993) were carried out study on the effect of dispersing nanosize particles of Al_2O_3, SiO_2 and TiO_2 in water. The studies are made for the determination of thermal conductivity and viscosity of the nanofluid. Choi (1995) started the word ‘nanofluid’, who found high thermal conductivity values compared to the suspended particles that are of a millimetre or micrometre in size. Experiments in the literature are emphasizing on the theoretical prediction and measurement of thermal conductivity of the nanofluids. The evaluation of forced convection heat transfer coefficient is lead up by Pak and Cho (1998). Recent interest in the use of nanofluids for possible heat transfer augmentation has drawn the attention of many scholars. A review on preparation methods and challenges of nanofluids was presented by Sidik et al. (2014). Yu et al. (2007) provided the information about nanofluid applications in the transportation industry including vehicle cooling, electronic cooling, defence, space applications, nuclear system cooling, biomedicine and others to improve heat transfer and energy efficiency of thermal systems. Recent reviews on nanofluids for solar applications have been presented by Al-Shamani et al. (2014), Nagarajan et al. (2014) and Kasaeian et al. (2015).

The study of heat transfer enhancement for nanofluids with twisted tape is undertaken by a few researchers. Experiments with nanofluid are conducted by Sharma et al. (2009) and Sundar and Sharma (2010) for the determination of heat transfer coefficients in a tube and with tape inserts using Al_2O_3 applicable in the transition and turbulent range of Reynolds number, respectively. Wongcharee and Eiamsa-ard (2011) studied the heat transfer enhancement of CuO/water nanofluid (CuO nanoparticle dispersed in water) and twisted tape with an alternate axis under a laminar flow for concentrations between 0.3 % and 0.7 %. The study is continued with corrugated tube equipped with twisted tape under turbulent flow using the same nanofluid and concentration range by Wongcharee and Eiamsa-ard (2012). The research for nanofluid

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CHAPTER 3

METHODOLOGY

3.1 OVERVIEW

This chapter consists of research methodology for the heat transfer evaluation with TiO_2 and SiO_2 nanofluids in a tube with twisted tape. The aim of the chapter is to explain the nanofluid preparation, the stability of nanofluids, the methods of properties measurement, the design and instrumentation of the experimental setup, and the formulation of mathematical model. The chapter presents the steps of nanofluid preparation by the dilution technique. The stability testing is important to show the state of dispersion of suspended nanoparticles in the base of water. The testing includes the visual condition observation, pH measurement, electrical conductivity measurement and transmission electron microscopy (TEM). The methods of properties measurement for thermal conductivity and viscosity are presented in the chapter, whereas the density and specific heat of nanofluids are estimated using mixture relation. The experimental setup is designed and fabricated for flow of fluid in a tube with twisted tape. The functions of the various components are explained item wise. Finally, the chapter provides a detailed mathematical model formulation of the eddy diffusivity equation for application with nanofluid turbulent flow over twisted tape. The equation is applicable as the nanofluids considered in the range of concentration are assumed homogenous.

3.2 PREPARATION OF NANOFLUIDS

The nanofluids can be prepared by two different methods. The first approach is a one step process. The nanoparticles are synthesized and simultaneously dispersed in a base fluid. The process is done in one single step. It is recommended to prepare nanofluids with one step process for high thermal conductivity of metal particles in order to avoid oxidation effect. The second approach of nanofluid preparation is by the two step process. The nanofluids are prepared in two stages. The nanoparticles are produced in the form of powder in the first step. Then, the nanoparticle is dispersed to the base liquid to form a stable solution called nanofluids. However, the challenge of this approach is overcoming the agglomeration and stability of prepared nanofluids. The agglomeration of the particle will cause the nanoparticle to settle down faster.

TiO_2 and SiO_2 water based nanofluids were used in the present heat transfer analysis. It was commercially produced by US Research Nanomaterials, Inc for research purposes in the form of liquid suspension. The procured TiO_2 and SiO_2 nanofluids were prepared to a new concentration by dilution techniques. The technique was applied successfully by the previous researchers in their heat transfer evaluation for TiO_2 and SiO_2 nanofluids (Bontemps et al., 2008; Duangthongsuk and Wongwises, 2010 and Ferrouillat et al., 2011).

The procured nanofluids in Table 3.1 are available in weight percent concentration, ω. SiO_2 nanofluid with 99.99 % purity contains nanoparticles with average diameter of 22 nm. It was supplied with original concentration of 25 % weight concentration. TiO_2 nanofluid with 99 % purity consumes TiO_2 nanoparticles with the diameter of 50 nm and original weight concentration of 40 %. The initial pH of TiO_2 and SiO_2 nanofluids were 6.5 and 11, respectively. The basic expressions for concentration of nanofluids by volume percent, ϕ and weight percent, ω are represented by Eqs. (3.1) and (3.2), respectively. The nanofluids in weight concentration, ω is converted to volume concentration, ϕ using Eq. (3.3). The new expression in Eq. (3.3) was derived by Eqs. (3.1) and (3.2). The previously published literatures for nanoparticle properties are given in Table 3.2.

$$\omega = \frac{m_p}{m_p + m_w} \times 100 \tag{3.1}$$

$$\phi = \left(\frac{m_p}{\rho_p}\right) \Big/ \left(\frac{m_p}{\rho_p} + \frac{m_w}{\rho_w}\right) \times 100 \tag{3.2}$$

$$\phi = \frac{\omega \rho_w}{\frac{\omega}{100}\rho_w + \left(1 - \frac{\omega}{100}\right)\rho_p} \tag{3.3}$$

Table 3.1: Properties of nanofluids supplied by US Research Nanomaterials, Inc

Type of nanofluid	**Diameter, (nm)**	**Weight concentration, ω (%)**	**Volume concentration, ϕ (%)**
TiO_2	50	40	13.62
SiO_2	22	25	13.06

Table 3.2: Physical properties of metal and metal oxide nanomaterials

Nanoparticle	**Thermal Conductivity, W/m.K**	**Density, kg/m^3**	**Specific heat, J/ kg.K**	**References**
Al_2O_3	36	3880	773	Pak and Cho (1998)
Cu	383	8954	386	Kothandaraman and Subramanyam (2007)
CuO	69	6350	535	Fotukian and Nasr Esfahany (2010)
Fe_3O_4	80.4	5180	670	Sundar et al. (2012)
SiC	490	3160	675	Kothandaraman and Subramanyam (2007)
SiO_2	1.4	2220	745	Vajjha et al. (2010)
TiO_2	8.4	4175	692	Pak and Cho (1998)
ZnO	29	5600	514	Vajjha and Das (2009), Hong et al. (2007)
ZrO_2	1.7	5500	502	Kothandaraman and Subramanyam (2007)