HEAT TRANSFER ENHANCEMENT OF BIOGLYCOL/WATER BASED TiO_2 AND SiO_2 NANOFLUIDS IN A FLAT TUBE WITH TWIN TWISTED TAPES

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Dedicated to my beloved wife Dr. Hind Mahmood Khudhur

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LIST OF SYMBOLS

A	Constant
A^+	Constant in van Driest expression
A_s	Heat transfer surface area, m^2
α_{nf}	Thermal diffusivity of nanofluid
α_p	Thermal diffusivity of particle
α_{bf}	Thermal diffusivity of base fluid
α	Conductivity ratio, $\alpha = (\sigma_p/\sigma_{bf})$
B	Constant
b	Bulk
β	Ratio of nanolayer thickness to particle radius
C_{nf}	Specific heat of nanofluid
C_p	Specific heat of particle
C_{pbf}	Specific heat of base fluid
C_{pf}	Specific heat of fluid
d_{bf}	Equivalent diameter of a base fluid molecule
d_{max}	Maximum particle size
d_p	Particle diameter
e	Plain flat tube
f	Darcy friction factor = $\Delta P/((L/D_h)(\rho U^2/2))$
f_{SL}	Friction factor of Smithberg and Landis
f_B	Blasius friction factor
f_{nf}	Friction factor of nanofluid
H	Flat tube height, m

h	Heat transfer coefficient, $Wm^{-2} K^{-1}$
I	Current, A
I_t	Turbulent intensity
k	Coefficient in eddy diffusivity equation of van Driest
K_B	Boltzmann constant
K_{eff}	Effective thermal conductivity
K_{bf}	Thermal conductivity of the base fluid
K_p	Thermal conductivity of the particle
K_{neff}	Net effective thermal conductivity
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 base fluid ratio, (K_{nf} / K_{bf})
L	Length of the test section, m
M	Molecular weight of the base fluid
$\dot{m}$	Mass flow rate, Kg/s
m_p	Mass of particle
m_{bf}	Mass of base fluid
μ	Fluid dynamic viscosity, kg s^{-1} m^{-3}
μ_r	Ratio of nanofluid to water viscosity
μ_{nf}	Absolute viscosity of nanofluid
μ_{bf}	Absolute viscosity of base fluid
N	Avogadro number
n	Empirical shape factor
Nu	Nusselt number = hD_h/k

Nu_{nf}	Nusselt number of nanofluid
Nu_{bf}	Nusselt number of base fluid
P	Pressure of flow in tube, Pa
p	Particle
pp	Pumping power
Pr	Prandtl number = $\mu Cp/k$
Pr_{bf}	Prandtl number of base fluid
Pr_{nf}	Prandtl number of nanofluid
Pe_{d}	Peclet number of particle
Δp	Pressure drop, Pa
Q	Heat transfer rate, W
q	Heat flux, W/m^2
Re	Reynolds number = $\rho UD_h/\mu$
r	Radius of aggregates nanoparticles
ρ	Density, kg/m^3
r_a	Radius of primary nanoparticles
ρ_{bf}	Density of base fluid
ρ_p	Density of particle
δ	Thickness of strip
t	Thickness of the test tube, m
T	Temperature, ^{o}C
T_b	Bulk temperature
T_{bi}	Inlet bulk mean temperature
T_{bo}	Oulet bulk mean temperature
T_{nf}	Temperature of nanofluid

τ	Shear stress
U	Average axial flow velocity, m s^{-1}
u	Velocity, m s^{-1}
V	Voltage, V
V_1	Initial volume
V_2	Final volume
$\bar{V}$	Volume flow rate, m^3 s^{-1}
ΔV	Volume of distilled water for dilution
υ	Kinematic viscosity
υ_{nf}	Kinematic viscosity of nanofluid
W	Flat tube width, m
w	Tape width, m
ω	Weight concentration in percent
η	Thermal enhancement index
γ	Ratio of thermal conductivity of the layer to particle
ϕ	Volume concentration in percent
φ	Volume concentration in fraction
φ_m	Maximum volume concentration in fraction
φ_i	Solid volume fraction of agglomerations
ψ	Sphericity
y	Twist pitch, m
y'	Distance measured normal to the wall
y^+	Dimensionless distance measured normal to the wall, $\left(\frac{y'u^*}{v}\right)$
ξ	Prandtl exponent

LIST OF ABBREVIATION

CC-QTs	Quadruple counter tapes as counter-quadruple swirl flow generators
CTT	Counter twisted tapes
COT	Co-counter twisted tape
BG	Bio glycol
EG	Ethylene glycol
PG	Propylene glycol
ID_h	Inside hydraulic diameter of the test tube, m
OD_h	Outer hydraulic diameter of the test tube, m
O-DTs	Overlapped dual twisted tapes
ID_h	Inner hydraulic diameter of the test tube, m
RANS	Reynolds-Averaged Navier-Stokes
RNG	Renormalization Group theory
TEM	Transmission electron microscopy
TKE	Turbulent kinetic energy
TT	Twisted Tape

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ABSTRAK

Penyelidikan tentang pemindahan haba telah mendapat perhatian penting sejak dahulu dan mendapati aplikasi dalam beberapa bidang seperti penyejukan peranti elektronik, sistem pembuatan dan sistem tenaga solar. Efektif kaedah pasif untuk pemindahan haba pembesaran adalah teknik tambahan untuk bendalir nano dan aliran pusaran peranti, sudah mempunyai perhatian yang besar dalam usaha untuk meningkatkan prestasi haba penukar haba. Antara peranti aliran pusaran yang digunakan untuk mewujudkan pusaran atau aliran menengah, memasukkan terpiuh pita adalah sangat popular kerana prestasi yang baik haba mereka. Permintaan yang semakin meningkat untuk cecair pemindahan haba yang lebih cekap dalam banyak aplikasi telah membawa kepada meningkatkan pemindahan haba untuk memenuhi cabaran penyejukan yang diperlukan. Bendalir nano, agak bahan kejuruteraan baru yang terdiri daripada bahan tambahan nanometer bersaiz dan cecair asas, telah mendapat perhatian meluas kerana ia adalah peranan dalam meningkatkan kecekapan sistem haba. Tujuan kajian ini adalah untuk menilai nombor Pekali pemindahan haba dan kejatuhan tekanan TiO_2 berdasarkan BioGlycol / Air dan bendalir nano SiO_2 untuk aliran dalam tiub yang rata dan dengan pita berpintal berkembar uji kaji dan berangka. Untuk penilaian ini, sifat-sifat termofizikal TiO_2 dan SiO_2 bendalir nano diperlukan semasa kepekatan dan suhu yang berbeza. Ikatan ujian adalah rekaan dengan kemudahan untuk memanaskan cecair dengan membalut dengan dua pemanas nikrom pada tiub rata dengan pilihan untuk memasukkan pita berpintal. Percubaan kari untuk menentukan nombor Nusselt dan faktor geseran dengan BioGlycol / air dengan nisbah campuran (20/80) % oleh TiO_2 jumlah berasaskan dan bendalir nano SiO_2 di (30, 50 dan 70 ^oC) dalam julat bergelora nombor Reynolds (Re) untuk aliran dalam tiub rata dan dengan pita berpintal kembar. Peningkatan maksimum dalam pemindahan haba adalah 28.2 % bagi 1.0 % bendalir nano TiO_2 di (Re = 21,194) dan suhu 50 ^oC. Walau bagaimanapun, peningkatan maksimum dalam pemindahan haba adalah 29.3 % daripada bendalir nano SiO_2 dengan kepekatan jumlah 2.0 % pada (Re = 21,169). Ia boleh menyatakan bahawa peningkatan dalam pemindahan haba bergantung kepada kepekatan dan operasi suhu nanofluid itu. Peningkatan pekali pemindahan haba dan faktor geseran dengan penurunan dalam nisbah twist untuk BioGlycol / air dan bendalir nano diperhatikan dari eksperimen. Peningkatan pemindahan haba maximume SiO_2 pada 2.0 % kepekatan jumlah dan 50 ^oC dengan kaunter pita berpintal (CTT-5) dan bersama-counter pita berpintal (COT-5) dengan nisbah twist 5 sehingga 129 % dan 113 % masing-masing lebih tinggi daripada tiub rata BioGlycol/air. Tambahan pula, dengan menggunakan TiO_2 nanofluid dengan 1.0 % kepekatan jumlah pada 50 ^oC dengan (CTT-5) dan (COT-5) memberi penambahan pemindahan haba maksimum sehingga 124 % dan 106 % masing-masing lebih tinggi daripada tiub rata BioGlycol / water. For yang kes tiub biasa, ia adalah lebih baik untuk mempunyai aliran TiO_2 dan SiO_2 bendalir nano pada 1.0 % dan 2.0 % jumlah kepekatan masing-masing. Sementara itu, bagi aliran nanofluid dengan pita berpintal, ia adalah disyorkan untuk menggunakan nisbah piuh 5. Penggunaan bendalir nano TiO_2 dengan pita berpintal adalah lebih baik untuk kepekatan jumlah sehingga 1.0 %. Walau bagaimanapun, penggunaan bendalir nano SiO_2 dengan pita berpintal tidak digalakkan disebabkan indeks peningkatan haba yang lebih rendah berbanding dengan aliran nanofluid dalam tiub yang nyata.

ABSTRACT

The research on heat transfer has been receiving important attention since long time ago and has found applications in several areas such as the cooling of electronic devices, manufacturing systems and solar energy systems. The effective passive methods for heat transfer augmentation are the additive technique for nanofluid and swirl flow devices, are acquiring great attention in order to enhance the thermal performance of the heat exchangers. Among the swirl flow devices which are used to create swirl or secondary flow, twisted-tape inserts are very popular because of their good thermal performance. The increasing demand for more efficient heat transfer fluids in many applications has been led to enhance heat transfer to meet the cooling challenge necessary. Nanofluid is a relatively new engineering material consisting of the nanometre-sized additives and base fluids, has gained extensive attention due to its role in improving the efficiency of thermal systems. Although, there are many studies of nanofluids with different types of base fluid such as water, Ethylene glycol (EG) and Propylene glycol (PG), there are very limited studies of using nanofluids with BioGlycol as a base fluid. While, BioGlycol (BG) showed more advantages compared to water Ethylene glycol (EG) and Propylene glycol (PG), for instance, a much lower freezing point and higher boiling point than water, provided lower viscosity compared to Propylene glycol (PG) and Ethylene glycol (EG), has greater thermal stability while possessing similar or better thermophysical properties compared to Propylene and Ethylene glycols and non-toxic renewable sourced fluid. The aim of the present study is to evaluate the heat transfer coefficient and pressure drop of BioGlycol/Water based TiO_2 and SiO_2 nanofluids for flow in a flat tube and with twin twisted tapes experimentally and numerically. For this evaluation, the thermophysical properties of TiO_2 and SiO_2 nanofluids are prepared at different volume concentrations and temperatures. A test rig was fabricated with the facility to heat the liquid by wrapping with two nichrome heaters on the flat tube with an option to insert the twisted tapes. Experiments are carried out to determine the Nusselt number and friction factor with BioGlycol/water of (20/80)% mixture ratio by volume based TiO_2 and SiO_2 nanofluids at (30, 50 and 70^{o}C) in the turbulent range of Reynolds number (*Re*) for flow in a flat tube and with twin twisted tapes. The maximum enhancement in the heat transfer was 28.2% for 1.0% TiO_2 nanofluids at *Re* = 21,194 and temperature 50^{o}C. However, the maximum heat transfer enhancement was 29.3% of SiO_2 nanofluids with 2.0% volume concentrations at *Re* = 21,169. It can be stated that the heat transfer enhancement depends on the nanoparticles concentration and operating temperature of the nanofluid. An increase in the Nusselt number and friction factor with a decrease in twist ratio for BioGlycol/water and nanofluids was observed from the experiments. The maximum heat transfer enhancement of SiO_2 at 2.0% volume concentration and 50^{o}C with counter twisted tapes (CTT-5) and co-counter twisted tapes (COT-5) with twist ratio of 5 were up to 129% and 113% respectively higher than the flat tube of BioGlycol/water. Furthermore, using the TiO_2 nanofluid with 1.0% volume concentration at 50^{o}C with (CTT-5) and (COT-5) gave the maximum heat transfer enhancement up to 124% and 106 % respectively higher than the flat tube of BioGlycol/water. For the case of plain tubes, it is preferable to have the flow of TiO_2 and SiO_2 nanofluids at 1.0% and 2.0% volume concentrations, respectively. Meanwhile, for the nanofluid flow with twisted tapes, it is recommended to use the twist ratio of 5. The use of TiO_2 nanofluid with twisted tapes is preferable for volume concentrations up to 1.0%. However, the use of SiO_2 nanofluid with twisted tapes is not recommended due to the lower thermal enhancement index compared to the nanofluid flow in plain tubes.

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LIST OF PUBLICATION

The list of publication that is carried out during the present study:

List of Journals

ISI Indexed Journal

1. **Abdolbaqi, M.K.**, Azmi, W.H., Mamat, R., Sharma, K.V. and Najafi, G., 2016. Experimental investigation of thermal conductivity and electrical conductivity of BioGlycol–water mixture based Al_2O_3 nanofluid. *Applied Thermal Engineering*, *102*, pp.932-941. **Published Q1 (IF=3.043)**

2. **Abdolbaqi, M.K.**, Sidik, N.A.C., Aziz, A., Mamat, R., Azmi, W.H., Yazid, M.N.A.W.M. and Najafi, G., 2016. An experimental determination of thermal conductivity and viscosity of BioGlycol/water based TiO_2 nanofluids. *International Communications in Heat and Mass Transfer*, *77*, pp.22-32. **Published Q1 (IF=2.559)**

3. **Abdolbaqi, M.K.**, Sidik, N.A.C., Hamzah, W.A.W. and Mamat, R., 2016. An experimental determination of thermal conductivity and electrical conductivity of bio glycol based Al_2O_3 nanofluids and development of new correlation. *International Communications in Heat and Mass Transfer*, *73*, pp.75-83. **Published Q1 (IF=2.559)**

4. **Abdolbaqi, M.K.**, Sidik, N.A.C., Mamat, R. and Hamzah, W.A.W., 2015. Experimental and numerical study of thermo-hydraulic performance of circumferentially ribbed tube with Al_2O_3 nanofluid. International Communications in Heat and Mass Transfer, 69, pp.34-40. **Published Q1 (IF=2.78)**

5. **Abdolbaqi, M.K.,** Azmi, W.H., Mamat, R., Mohamed, N.M.Z.N. and Najafi, G., 2016. Experimental investigation of turbulent heat transfer by counter and co-swirling flow in a flat tube fitted with twin twisted tapes. *International*

Communications in Heat and Mass Transfer, *75*, pp.295-302. **Published Q1 (IF=2.559)**

6. **Abdolbaqi, M.K.,** Sidik, N.A.C., Rahim, M.F.A., Mamat, R., Azmi, W.H., Yazid, M.N.A.W.M. and Najafi, G., 2016. Experimental investigation and development of new correlation for thermal conductivity and viscosity of BioGlycol/water based SiO_2 nanofluids. *International Communications in Heat and Mass Transfer*, *77*, pp.54-63. **Published Q1 (IF=2.559)**

7. **Abdolbaqi, M.K.,** Mamat, R., Sidik, N.A.C., Azmi, W.H. and Selvakumar, P., 2017. Experimental investigation and development of new correlations for heat transfer enhancement and friction factor of BioGlycol/water based TiO_2 nanofluids in flat tubes. *International Journal of Heat and Mass Transfer*, *108*, pp.1026-1035. **Published Q1 (IF=2.857)**

8. **Abdolbaqi, M.K.,** Sidik, N.A.C., Mamat, R., Azmi, W.H., 2016. Experimental determination for heat transfer enhancement and friction factor of Bio Glycol/water based SiO_2 nanofluid in flat tube. *International Journal of Thermal Sciences* **Under review Q1 (IF=2.769)**

9. **Abdolbaqi, M.K.,** Sidik, N.A.C., Mamat, R., Azmi, W.H., 2016. Experimental and numerical investigation of turbulent nanofluid heat transfer by counter and co-swirling flow in a flat tube fitted with twin twisted tapes. *Applied Thermal Engineering*. **Under review Q1 (IF=3.043)**

SCOPUS Indexed Journals:

10. **Abdolbaqi, M.K.,** Azwadi, C.S.N. and Mamat, R., 2014. Heat transfer augmentation in the straight channel by using nanofluids. *Case Studies in Thermal Engineering*, *3*, pp.59-67. **Published.**

11. **Abdolbaqi, M.K.,** Azwadi, C.S.N., Mamat, R., Azmi, W.H. and Najafi, G., 2015. Nanofluids heat transfer enhancement through straight channel under

turbulent flow. *International Journal of Automotive and Mechanical Engineering*, 11, p.2294. **Published.**

12. **Abdolbaqi, M.K.,** Azwadi, C.S.N., Mamat, R., Azmi, W.H., 2016 Experimental and numerical investigation of heat transfer augmentation using ethylene glycol/ water based Al_2O_3- nanofluids under turbulent flow in a flat tube. Jurnal Teknologi. *58 pp.85–88.* **Published.**

Non-indexed Journals:

13. **Abdolbaqi, M.K.,** MAMAT, R. and SIDIK, N.A.C., 2014. The Effects of turbulent nanofluids and secondary flow on the heat transfer through a straight channel. *Recent Advances in Mathematical and Computational Methods.* pp.118-124. **Published.**

14. **Abdolbaqi, M.K.,** Mamat, R., Azmi, W.H., 2015. Computational Fluid Dynamics study of heat transfer enhancement in a circular tube using nanofluid. *International journal of engineering technology and sciences*. 3(1): pp.1-7. **Published.**

15. Alawi, O.A., Sidik, N.C., Kazi, S.N. and **Abdolbaqi, M.K.,** 2016. Comparative study on heat transfer enhancement and nanofluids flow over backward and forward facing steps. *J. Adv. Res. Fluid Mech. Therm. Sci*, *23*, pp.25-49. **Published.**

List of Conference Proceedings:

16. **Abdolbaqi, M.K.,** Mamat, R., Azmi, W.H. Computational Fluid Dynamics study of heat transfer enhancement in a circular tube using nanofluid. *In*: National conference of postgraduate Research, 2014, 26-27 November, UMP, Gambang, Malaysia

17. **Abdolbaqi M. Kh.,** Nor Azwadi Che Sidik, Rizalman Mamat, W. H. Azmi, 2014. Nanofluids Heat Transfer enhancement through straight channel under turbulent flow. In: International conference on automotive innovation and green energy vehicle, 2014, 26-27August, Kuantan, Pahang, Malaysia

18. **Abdolbaqi M. Kh.,** Nor Azwadi Che Sidik, Rizalman Mamat, W. H. Azmi, Hind M. Kh. Experimental and Numerical investigation of Heat transfer enhancement using Al_2O_3-Ethylene Glycol/Water nanofluids in straight channel. *In*: National conference of postgraduate Research, 2016, 27-28 September, UMP, Pekan, Malaysia