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HEAT TRANSFER AND TURBULENT NANOFLUID FLOW INVESTIGATION OVER MICROSCALE BACKWARD-FACING STEP

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By

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Chairman : Abd Rahim Abu Talib, PhD
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Flow separation and re-connection play important roles in many different fields. The continued increase in functionality and compactness in these fields and devices such as the microchannel, micro heat-exchangers. In the present study, experimental and numerical simulation using computational fluid dynamics (CFD) is applied to study the steady-state convective turbulent nanofluids and hybrid nanofluids flow over two-dimensional (2D) microscale backward-facing step (MBFS) placed in a channel. In this research, the wall downstream of the channel was maintained at a uniform heat flux, while the straight wall that forms the other side of the duct was maintained at a constant temperature equal to inlet fluid temperature. The upstream wall and the step wall were considered adiabatic surfaces. The expected valid trend of step height (*S*) length scale is considered in the range of $200 \leq S \leq 500$ μm for the numerical study. The Reynolds number (*Re*) range in the study of $5{,}000 \leq Re \leq 10{,}000$. All the other walls including the step were considered adiabatic. The step height was $S = 500$ μm in the experimental study. Different types of nanoparticles such as CuO and βGa_2O_3 with a volume fraction (φ) of $1\% \leq \varphi \leq 4\%$ are dispersed in the water. Moreover, hybrid nanoparticles of CuO and βGa_2O_3 with 4% volume fraction have been applied in this study. To ensure the purity of CuO and βGa_2O_3 nanoparticles SEM, particle size distribution, and XRD characterizations have been applied. The outcomes reveal that the gradients in the Nusselt number (*Nu*) inside the recirculation region increase by increasing the *S*. It also appears that increasing the *S* decreases the pressure-drop and *Re*. Heat transfer rate enhances with an increase in any of the parameters of volume fraction (φ) and Reynolds number (*Re*). Also, the friction factor has a significant consequence on the rate of heat transfer and characteristics of the flow at a constant *Re*. Besides, the outcomes revealed the friction factor increased by increasing the volume fraction. The hybrid nanofluids of βGa_2O_3-CuO /water have a higher value of *Nu* in comparison with βGa_2O_3/water and CuO

/water. However, the nanofluid of βGa_2O_3/water enhances the heat transfer rate in comparison with CuO/water nanofluid. Overall, the results showed promising outcomes of utilizing nanoparticles in the separation flow to enhance the heat transfer to the industry that relies on the heat transfer as the main goal to achieve such as heat exchanger.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah.

PENYIASATAN TERHADAP PEMINDAHAN HABA DAN ALIRAN BENDALIR NANO BERGELORA MELALUI LANGKAH SKALA MIKRO PANDANGAN BELAKANG

Oleh

ALBUHAMDAN SADEQ SALMAN ABED

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Pemisahan aliran dan penyambungan semula memainkan peranan penting dalam pelbagai bidang. Peningkatan fungsi dan pemampatan yang berterusan dalam bidang ini seperti saluran mikro, dan penukar haba mikro. Dalam kajian ini, simulasi eksperimen dan berangka menggunakan komputasi dinamik bendalir (CFD) diaplikasikan untuk mengkaji keadaan bendalir nano bergelora konvektif stabil dan aliran bendalir nao hibrid melalui langkah skala mikro pandangan belakang dua dimensi (2D). Dalam penyelidikan ini, dinding hilir saluran dikekalkan pada fluks panas yang seragam, sementara dinding lurus yang membentuk sisi lain saluran dikekalkan pada suhu tetap sama dengan suhu bendalir masuk. Dinding hulu dan dinding tangga dianggap permukaan adiabatik. Skala panjang ketinggian langkah (*S*) yang dapat dipertimbangkan dalam lingkungan $200 \leq S \leq 500$ µm untuk kajian berangka. Nombor Reynolds (*Re*) adalah diantara $5{,}000 \leq Re \leq 10{,}000$. Semua tembok lain adalah sama. Ketinggian langkah adalah $S = 500$ µm di dalam kajian eksperimen. Jenis partikel nano yang berlainan seperti CuO dan βGa_2O_3 dengan pecahan isipadu (φ) $1\% \leq \varphi \leq 4\%$ tersebar di dalam air. Selain itu, partikel nano hibrid CuO dan βGa_2O_3 dengan pecahan isi padu 4% telah digunakan dalam kajian ini. Untuk memastikan ketulenan partikel nano CuO dan βGa_2O_3 SEM, taburan saiz zarah, dan ciri XRD telah diterapkan. Hasilnya menunjukkan bahawa kecerunan dalam nombor Nusselt (*Nu*) di dalam kawasan peredaran semula meningkat dengan peningkatan *S*. Ini juga kelihatan bahawa peningkatan *S* menurunkan tekanan *Re*. Pemindahan haba meningkat secara laju dengan peningkatan salah satu parameter pecahan isipadu (φ) dan bilangan Reynolds (*Re*). Selain itu, faktor geseran adalah berkesan terhadap kadar pemindahan haba dan ciri aliran pada *Re* yang tetap. Justeru, menunjukkan faktor geseran meningkat dengan meningkatkan pecahan isipadu. Bendalir nano hibrid βGa_2O_3-CuO / air mempunyai nilai *Nu* yang lebih tinggi berbanding dengan βGa_2O_3/air dan CuO/air. Walau bagaimanapun, bendalir nano βGa_2O_3/air meningkatkan kadar pemindahan haba berbanding dengan bendalir

nano CuO/air. Secara keseluruhannya menunjukkan hasil yang dijanjikan dari penggunaan partikel nano dalam aliran pemisahan untuk meningkatkan pemindahan haba ke industri yang bergantung pada pemindahan haba sebagai tujuan utama untuk dicapai seperti penukar haba.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF NOMENCLATURES

AR	Aspect ratio
Cp	Specific heat, (J/kg.K)
C_f	Friction coefficient
D	Normalised distance of the baffle
Dh	Hydraulic diameter, µm
E	Young's modulus, kg /m. s^2
ER	Expansion ratio
Gr	Grashof numbers, $g\beta q w s^4/(k\upsilon^2)$
H	Duct's height downstream, µm
Ha	Hartmann number
JF	Performance evaluation criterion
k	Thermal conductivity, W/m.K
Kn	Knudsen number
L_1	Upstream Wall length, mm
L_2	Downstream Wall length, mm
Ns	Entropy generation
Nu	Nusselt number
Pr	Prandtl number, v_f/α_f
Pr_t	Turbulent Prandtl number
q_w	Uniform heat flux, W/m^2
Ra	Rayleigh number
Re	Reynolds number
Ri	Richardson number

S	Step height, μm
St	Stanton number
T	Temperature, k
ΔT	Temperature difference
u_∞	Average velocity velocity, m/s
W	Width of the duct, mm

LIST OF GREEK SYMBOLS

φ	Volume fraction of nanoparticle
γ	Inclined angle
ξ	Thermal performance criterion
ϖ	Non-dimensional frequency
ρ	Density, kg/m^3
ν_f	kinematic viscosity of fluid, m^2/s
μ	Viscosity, $N.s/m^2$
B	Thermal expansion coefficient, $1/K$
α_f	Thermal diffusion of fluid, $N.s/m^2$

LIST OF ABBREVIATIONS

AuNP	Gold nanoparticles
BFS	Backward-facing step
CNT	Carbon Nanotube
CuNP	Copper nanoparticles
DW	Delta wing
DWCNT	Double-wall carbon nanotube
DWP	Delta wing pair
FVLBM	Finite volume lattice Boltzmann method
MBFS	Microscale backward-facing step
MWCNT	Multiwall carbon nanotube
ND-Ni	Nano diamond-nickel
LBE	Lead-bismuth eutectic
LDV	Laser doppler velocimetry
LSFEM	Least-squares finite-element method
PCM	Phase change material
PIV	Particle image velocimetry
PPY	Polypyrrole
RKF	Runge–Kutta–Fehlberg
RKF45	Runge–Kutta–Fehlberg fourth-fifth
SDS	Sodium Dodecyl Sulfate

CHAPTER 1

INTRODUCTION

1.1 Background

Flow separation and re-connection are critical for the design of many engineering items involving heating or cooling. The Backward-facing step (BFS) has been designed for a wide range of applications in which heat transfer is the core of the step, such as electronic equipment, environmental inspection systems, combustion chambers, electrical systems, valve flow, and turbine blade cooling passes (Gavasane *et al.*, 2018). Nevertheless, the flow separation phenomenon was not requested for different engineering fields because of energy loss, and the pressure drop needed further pumping power to solve these problems (Togun, 2016, Mohammed *et al.*, 2016; Mohammed *et al.*, 2017;).

Numerous backward-facing step (BFS) studies have been conducted in different parameters and flow regimes experimentally and numerically. Some of these studies have examined the impacts of step height (*S*) on the characteristics of the heat transfer in various flow regimes. The results of *S* have been obtained by Abu-Mulaweh *et al.*, (Abu-Mulaweh *et al.*, 1993a; Abu-Mulaweh *et al.*,1993b, 1995; Abu-Mulaweh *et al.*, 2002), and the study of Nie and Armaly, (2002), which relied on the experimental research of Armaly *et al.*, (2002). Furthermore, Chen *et al.*, (2006) have examined the effect of *S* in BFS in turbulent and laminar regimes. In the microscale backward-facing step (MBFS), a numerical study has held by Kherbeet *et al.*, (2014b) examined the influence of *S* in the regime of the laminar flow. All the mentioned studies above have revealed that the *S* has a significant impact on the characteristics of the fluid flow and heat transfer.

In nanofluid studies, many researchers have investigated the nanoparticles in the traditional fluids over backward-facing step (BFS) (Abu-Nada, 2008a; Al-aswadi *et al.*, 2010; Mohammed *et al.*, 2011; Kherbeet *et al.*, 2012; Mohammed *et al.*, 2012, Kherbeet *et al.*, 2014; Kherbeet *et al.*, 2015; Selimefendigil and Öztop, 2015, 2018; Alawi *et al.*, 2016; Lv *et al.*, 2019; Nath and Krishnan, 2019;). The effect of the volume fraction (φ) examined in the heat transfer and fluid flow also been investigated. From the above studies, it has been confirmed that an increment in the Nusselt number (*Nu*), and the heat transfer rate were noticed when the volume fraction (φ) increased. However, other studies have revealed that by increasing the φ of the same nanoparticle caused a higher friction factor (Abu-Nada, 2008a; Kherbeet *et al.*, 2012; Kherbeet *et al.*, 2014; Lv *et al.*, 2019; Selimefendigil and Öztop, 2015, 2018). On the other hand, the effect of the nanoparticle diameter was conducted. The outcomes demonstrated that the diameter of the nanoparticles has an empirical impact on heat transfer improvement (Kherbeet *et al.*, 2012; Kherbeet *et al.*, 2015;).

In the present research, the turbulent flow of different nanofluids over microscale backward-facing step (MBFS) have been conducted. Furthermore, the present study employs hybrid nanofluid on the MBFS. Moreover, a comparison of nanofluids and hybrid nanofluids as well as their impact on the heat transfer enhancement as well as the flow characterization haven been conducted.

1.2 Problem definition

Flow separation and reattachment phenomena have taken place in many thermal systems, and a lot of effort has been made to understand the hydrodynamics and thermal implications of these phenomena.

The continued increase in functionality and compactness of microelectronics in these devices and their modules, such as the microchannel, micro heat-exchangers, and their heat-transfer characteristics has also led to the present work. Besides, thermic control of microelectronic devices is a challenge because of the limited size of heat dissipation devices and the very high operating temperature requirements (Qu *et al.*, 2017).

Nanofluids and hybrid nanofluids are a new class of heat transfer fluids that consist of mix suspended nanoparticles that have better stability. The base fluids such as water, ethylene glycol, glycerin, and engine oil play important roles in the heat transfer of many industrial applications. However, the low thermal conductivity has always been the primary limitation in the development of energy-efficient heat transfer fluids. Further investigation needs to be done on the enhancement of the heat transfer using nanofluids and hybrid-nanofluid (Ramachandran *et al.*, 2016; Sidik *et al.*, 2016; Bhattad *et al., 2018).*

The majority of previous works in the last ten years are based on the traditional flow of fluid over the two-dimensional (2D) backward-facing step (BFS). However, only a few previous papers have covered the fluid flow and the transfer of heat through microscale backward-facing steps (Hsieh *et al.,* 2010; Kherbeet *et al.,* 2012; Kherbeet *et al.*, 2014; Kherbeet *et al.*, 2015; Kherbeet *et al.*, 2015; Gavasane *et al.*, 2018). While there is no study discussed utilizing nanoparticles over microscale backward-facing step (MBFS) channels under turbulent flow conditions (with flow separation) are typically excluded from the thermal analysis because of the high computational and experimental resources needed to study the problem.

To date, there is a lack of in-depth studies on nanofluid and hybrid nanofluid flows in the MBFS channel. Therefore, this study provides comprehensive data on these flows, which will assist thermal designers in designing micro heat exchangers with high thermal efficiency.

In general, the hybrid nanofluids and nanofluids flow and the characteristics of heat transfer on MBFS have been not investigated numerically and experimentally, thus has motivated the present research.

1.3 Aim of the study

The present work attempts to fulfill the existing gap in this area of research. The industrial applications of enhancing the heat transfer over microscale backward-facing step (MBFS) applying hybrid-nanofluid and nanofluids are to further develop the microelectronic cooling techniques, the micro heat exchanger, *etc*. Besides, the study purpose of answering the research questions which are framed to provide guidance to the research and to show the connection between the objectives and research questions as follows:

i. What is the best geometry, and step height for the microscale backward-facing step (MBFS) channels?
ii. Is the nanofluid used in the current research gives a significant thermal-hydraulic performance?
iii. Is the hybrid nanofluid conducts in the current study give considerable enhancement of heat transfer?
iv. What happens when the nanoparticle concentration is increased?
v. How significantly the turbulent flow on the heat transfer on the MBFS?

1.4 Objectives

The objectives of this research are:

i. To numerically investigate the effect of the steps on the turbulent mixed convective over a 2D microscale backward-facing step (MBFS).
ii. To experimentally examine the effects of different volume fractions of turbulent CuO/water nanofluid flow over MBFS.
iii. To experimentally inspect the impacts of turbulent βGa_2O_3/water nanofluid flow over the heat transfer characteristics on the MBFS.
iv. To experimentally and numerically comparison of hybrid nanofluid of βGa_2O_3-CuO/water and nanofluids of CuO/water and βGa_2O_3/water at 4% volume fraction on MBFS.

1.5 Research hypotheses

Guidelines for conducting research relevant to the problem statement are formulated as the research goals, certain assumptions, and hypotheses. These fundamental assumptions will be agreed upon for this analysis, which states that the turbulent flow over microscale backward-facing step channel will facilitate heat transfer in a variety of applications and devices, such as microchannel heat exchangers.

Not only can the nanofluids and hybrid nanofluid aid with heat transfer in microscale backward-facing step channel, but the volume fraction of each nanoparticle used also help to enhance the rate of heat transfer. The distinct fraction of the nanoparticle can influence the heat transfer rate as well as the coefficient of friction. It is assumed that when we use a high volume fraction, friction and pumping power will both increase.

1.6 Novelty

As far as the author knows, there have not yet been any scientific investigations that have attempted to examine the possible effects of hybrid nanofluids. This particular area of research is addressing the gap that exists in the literature. Additionally, there are no known studies of the impact of constant and variable properties in the Nusselt number (*Nu*) and friction factor (*f*).

Also, CuO/water, βGa_2O_3/water, and the hybrid nanofluid of βGa_2O_3- CuO / water turbulent flow have not been used before in heat transfer over microscale backward-facing step (MBFS) studies. The industrial applications of enhancing the heat transfer over MBFS are to develop the microelectronic cooling techniques, and the micro heat exchanger, etc.

The main novelties of this research are:

i. A numerical study using single-phase models of hybrid nanofluid and nanofluid turbulent flow over microscale backward-facing step (MBFS) to enhance the heat transfer.
ii. Experimental investigations of using turbulent nanofluids of CuO/water, βGa_2O_3/water, and βGa_2O_3- CuO / water over MBFS to enhance the heat transfer.

1.7 Scope of research

In the current study, the scope is the range of each objective's parameter. They are stated as follows:

1. The base fluid used in the numerical and experimental study over 2D microscale backward-facing steps (MBFS) was water.
2. In mathematical modeling, the RNG k- ε model was employed to simulate the turbulent flow regime.

3. The single-phase models were employed in the mathematical modeling to simulate the convective heat transfer of nanofluid and hybrid nanofluid flow in the MBFS channel.
4. βGa_2O_3, CuO nanoparticles have been used in the experimental and numerical investigations conducted on a 2D MBFS.
5. Different nanoparticle concentrations have been utilized in the current study which was from 1% - 4 % for the nanofluid preparation and 4% for the hybrid nanofluid.
6. The *Re* is varied from 5,000 to 10,000 to cover the turbulent flow regime.

1.8 Thesis outline

The current study chapters were structured in the subsequent style: Chapter 2 presents a broad literature review in the heat transfer enhancement field that used backward-facing step (BFS), nanofluids, and hybrid nanofluids. The factors that affect the performance of the nanofluids and hybrid nanofluids as well as the comparison studies between the nanofluids and the hybrid nanofluids. Chapter 3 shows the methods of solving the problem which includes mathematical modeling such as the governing equations, physical models and assumptions, and boundary conditions. Furthermore, the chapter presents the thermophysical properties of the nanofluids and hybrid nanofluids, numerical validations and grid-independent tests, and the experimental setup. Chapter 4 gives the details of the experimental and numerical outcomes which were discussed. Finally, Chapter 5 covers the conclusion and future work recommendations.

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APPENDICES

APPENDIX A-

Test Section

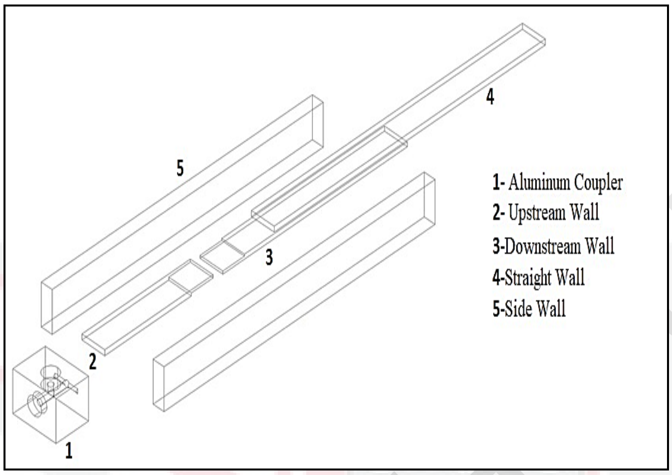


Figure A.1 : Test section parts

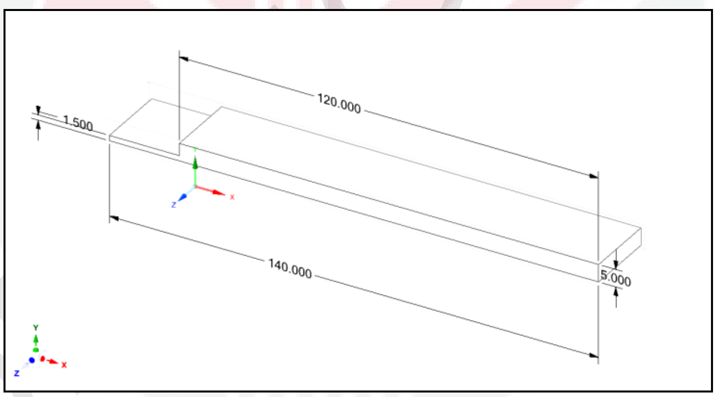


Figure A.2 : Downstream wall

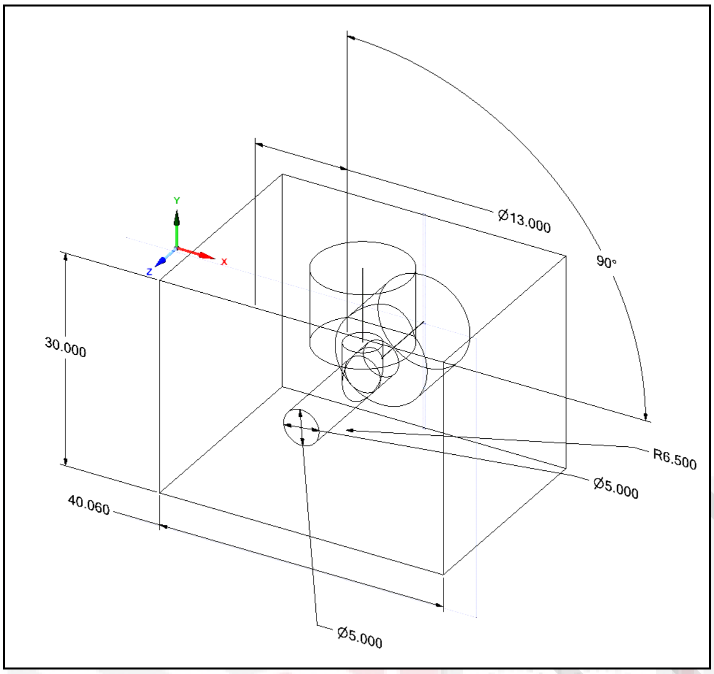


Figure A.3 : Aluminum coupler

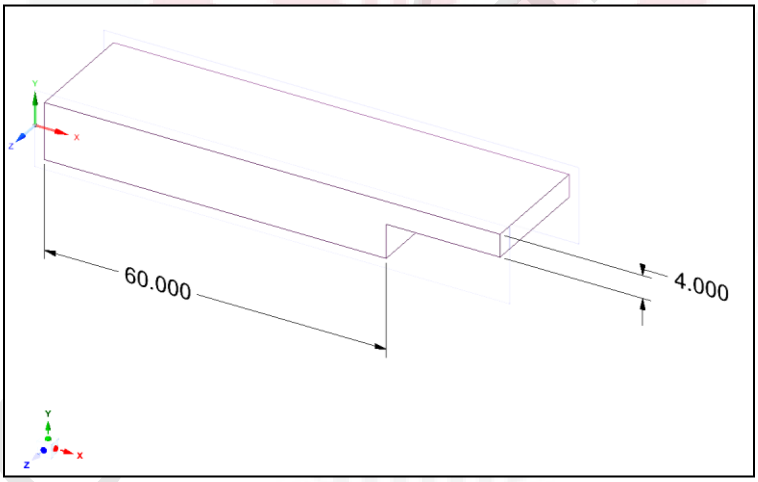


Figure A.4 : Upstream wall

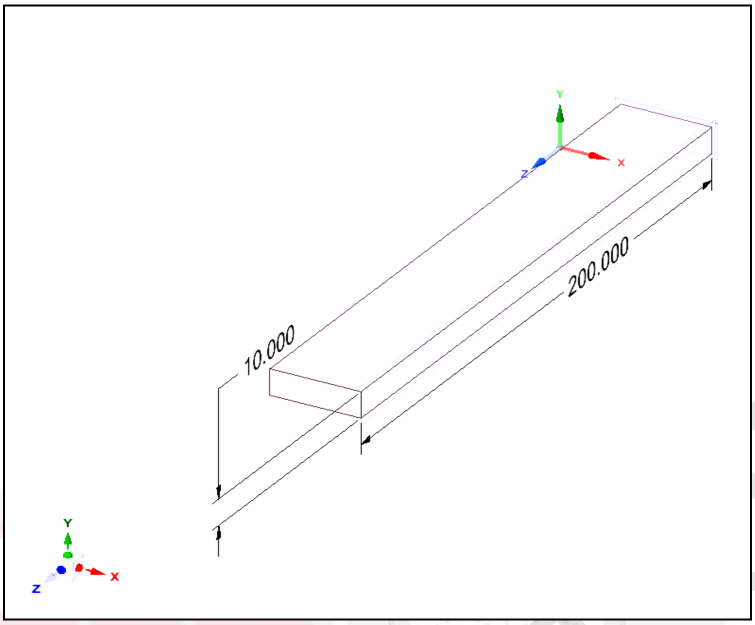


Figure A.5 : Side wall

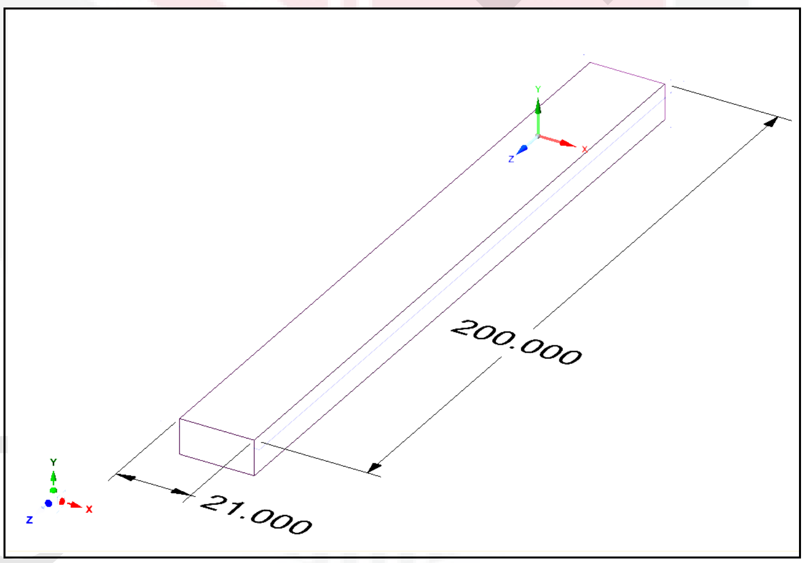


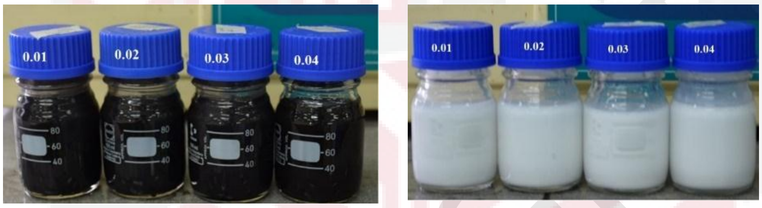
Figure A.6 : Straight wall

APPENDIX B

Nanofluid preparation and Experimental setup

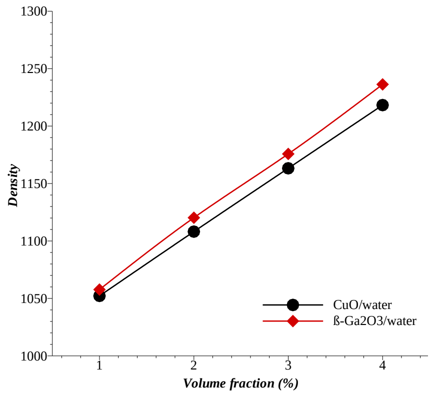
Table B.1 : Instruments used in the preparation

Instrument	Accuracy
Carbolite mechanical convection ovens	-
Ultrasonic device (Sonicator)	-
DA-130N density meter	± 0.001
Viscometer	± 0.03
Thermal conductivity KD2	± 0.01
Magnetic Stirrer	-
Balance HR-250 AZ	± 0.1

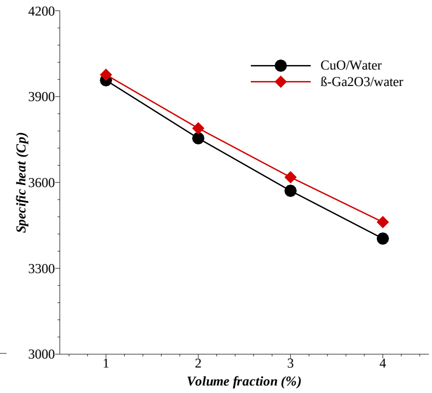


a- CuO/water　　**b-** βGa_2O_3/water

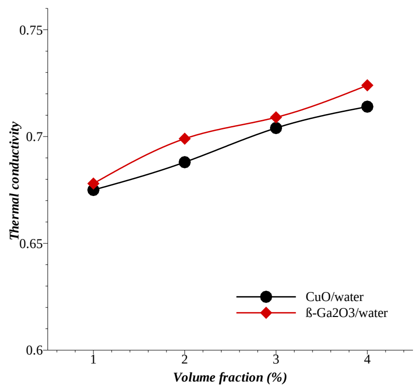
Figure B.1 : Prepared nanofluids



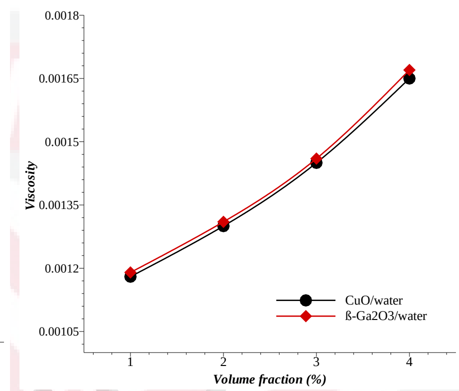
a- Density (Kg/m^3)



b- Specific heat (J/Kg.K)



c- Thermal conductivity (W/m.K)



e- Viscosity $(N.s/m^2)$

Figure B.2 : Nanofluids thermophysical properties

APPENDIX C

In the current research, the error values are recognizable for the values of the independent variables, which are (U_1, U_2, …, U_n), correspondingly. Consequently, the value of R can be estimated from the subsequent equations:

$$U_R = \pm\left[\sum_{i=1}^{n}\left(\frac{\partial R}{\partial x_i}U_{x_i}\right)^2\right]^{1/2}$$

Where the uncertainty value is U_{X_i} for parameter x_i.

$$Re = \frac{\rho.u.D_h}{\mu}$$

$$U_{Re} = \pm\left[\left(\frac{uD_h}{\mu}U_\rho\right)^2 + \left(\frac{\rho D_h}{\mu}U_u\right)^2 + \left(\frac{\rho u}{\mu}U_{D_h}\right)^2 + \left(\frac{-\rho u D_h}{\mu^2}U_\mu\right)^2\right]^{\frac{1}{2}}$$

$$U_{Re} = \pm\left[\left(\frac{uD_h}{\mu}U_\rho\right)^2 + \left(\frac{\rho D_h}{\mu}U_u\right)^2 + \left(\frac{\rho u}{\mu}U_{D_h}\right)^2 + \left(\frac{-\rho u D_h}{\mu^2}U_\mu\right)^2\right]^{\frac{1}{2}}$$

The friction factor uncertainty is resolved as follows:

$$f = \frac{\Delta p.D_h.2}{L.\rho.u_{ave}^2}$$

$$U_f = \pm\left[\left(\frac{2D_h}{L\rho u_{ave}^2}U_{\Delta p}\right)^2 + \left(\frac{2\Delta p}{L\rho u_{ave}^2}U_{D_h}\right)^2 + \left(\frac{-2\Delta p D_h}{L^2\rho u_{ave}^2}U_L\right)^2 + \left(\frac{-2\Delta p D_h}{L\rho^2 u_{ave}^2}U_\rho\right)^2 + \left(\frac{-2\Delta p D_h}{L\rho u_{ave}^4}Uu_{ave}\right)^2\right]^{\frac{1}{2}}$$

The Nusselt number uncertainty is defined as follows:

$$Nu = \frac{qD_h}{(T_w - T_b)k}$$

$$U_{Nu} = \pm\left[\left(\frac{D_h}{(T_w - T_b)k}U_q\right)^2 + \left(\frac{q}{(T_w - T_b)k}U_{D_h}\right)^2 + \left(\frac{-qDh}{(T_w - T_b)^2k}U_{T_w}\right)^2 + \left(\frac{qDh}{(T_w - T_b)^2k}U_{T_b}\right)^2 + \left(\frac{-qDh}{(T_w - T_b)k^2}U_k\right)^2\right]^{\frac{1}{2}}$$

BIODATA OF STUDENT

Sadeq Salman Abed Albuhamdan was born in Dhi Qar, Iraq, on 9th October 1991. He received his Bachelor of Science in Fuel and Energy Engineering from Southern Technical University (STU) in Basra, Iraq in September of 2013. His study of Master in Manufacturing Systems Engineering received from Universiti Putra Malaysia (UPM) in August 2017. His Master project was of corrosion in oil pipelines. He started preparing for the PhD degree in Universiti Putra Malaysia since February 2018. The PhD research titled 'Heat transfer and turbulent fluid flow over microscale backward-facing step' with Assoc. Prof. Ir. Ts. Dr. Abd. Rahim Bin Abu Talib. He can be contacted at sdq.sa91@gmail.com.

LIST OF PUBLICATIONS

Journal

Salman, S., Abu Talib, A.R., Hilo, A., Nfawa, S.R., Thariq, M., Sultan, H. and Saadon, S., 2019. Numerical Study on the Turbulent Mixed Convective Heat Transfer over 2D Microscale Backward-Facing Step. *CFD Lett.*, 10, pp. 31–45.

Salman, S., Abu Talib, A.R., Saadon, S. and Sultan, M.H., 2019. Hybrid nanofluid flow and heat transfer over backward and forward steps: A review. *Powder Technology*. 363: 448-472 (JCR Q1, I.F = 3.413)

Conference

Salman, S., A.R Abu Talib, Ali Hilo, Sadeq R. Nfawa, M.T.H. Sultan and S. Saadon (2019) Numerical Study on the Turbulent Mixed Convective Heat Transfer over 2D Microscale Backward-Facing Step, Presented at the SouthEast Asia Workshop on Aerospace Engineering (SAWAE), Aug 29-30, Kuala Lumpur Malaysia.