UNIVERSITI PUTRA MALAYSIA

NANOFLUID FLOW AND HEAT TRANSFER IN CORRUGATED BACKWARD-FACING STEP CHANNEL USING ETHYLENE GLYCOL AS BASED FLUID

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

August 2020

DEDICATION

This thesis is dedicated to everyone around me, especially those who have made significant contributions during the course of my PhD journey up to the completion of this thesis. Firstly, I would like to dedicate this work to my beloved parents, and all members of my family. Secondly, I would like to dedicate to this work to my supervisory committee, Professor Ir. Ts. Dr. Abd Rahim Abu Talib, Professor Ir. Ts. Dr. Mohamed Thariq Hameed Sultan, and Dr. Mohd Faisal Abdul Hamid for their valuable guidance throughout this research. Lastly, I dedicate this thesis to my family and all my friends for their true friendship and moral support, and for motivating me to complete this thesis.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman : Professor Ir. Ts. Abd Rahim Abu Talib, PhD
Faculty : Engineering

Experimental and numerical investigations are conducted to study the forced convection heat transfer and nanofluid flow through corrugated backward-facing step channels. Finite Volume Method (FVM) was used to solve the governing equation and the SIMPLE algorithm approach was applied. On 200 mm of the downstream wall, constant heat flux is applied, while the other walls are considered as isolated surfaces. Parameters such as corrugation shape (triangular, trapezoidal, and zigzag), amplitude height (1, 2, 3, 4, and 5 mm), pitch diameter (10, 20, 40, and 60 mm) and Reynolds number (*Re*) in the range of 5,000 to 20,000 were considered. The effect of CuO and MgO nanoparticles dispersed in pure ethylene glycol (EG) as a base fluid with diameters of 40 nm and volume concentrations of 0 to 5% on the fluid flow and heat transfer are investigated the length of the upstream wall of the channel was set to 200 mm and the length of the downstream wall was 300 mm. The height of the inlet and outlet were 10 mm and 20 mm, respectively. The expansion ratio is 2. The results reveal that combined a corrugated wall with a backward-facing step substantially improved the heat transfer, accompanied by a slight increment in the friction factor. The trapezoidal corrugated wall shows the highest enhancement in the heat transfer rate at 4 mm amplitude height and 20 mm pitch diameter. Combined the backward-facing step with corrugated wall enhanced the Nusselt number (*Nu*) up to 62% at Re = 5,000. The performance evaluation criteria increased as the amplitude height increases until it reached 4 mm and then decreased steeply.

Moreover, the experimental results indicated that the heat transfer coefficient increases as the volume fraction of nanoparticles increased. The CuO-EG nanofluid enhances the Nusselt number up to 11% compared to pure EG at a volume fraction of nanoparticles equal to 0.05. The friction factor of CuO nanofluid increases up to approximately 15% at volume fraction 0.01 and 0.03 and Reynolds number 5,000 and

decreases as the Reynolds number increases. The maximum value of the performance evaluation criterion reached is 1.5 at a volume fraction of nanoparticles equal to 0.03 for the case of CuO while it reaches 1.2 for the case of MgO nanofluid.

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

KAJIAN EKSPERIMEN DAN BERANGKA TERHADAP ALIRAN BENDALIR NANO DAN PEMINDAHAN HABA DALAM SALURAN LANGKAH PANDANGAN BELAKANG BERALUN MENGGUNAKAN ETHYLEN GLYCOL SEBAGAI BENDALIR ASAS

Oleh

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Kajian eksperimen dan berangka dilakukan untuk mengkaji pemindahan haba perolakan paksa dan aliran bendalir nano dalam saluran langkah pandangan belakang beralun. Kaedah Finite Volume (FVM) digunakan untuk menyelesaikan persamaan dan pendekatan algoritma SIMPLE digunakan. Pada 200 mm dinding hilir, fluks haba digunakan secara berterusan, sementara dinding lain dianggap sebagai permukaan terpencil. Parameter seperti bentuk bergelombang (segitiga, trapezoid, dan zigzag), tinggi jerayun (1, 2, 3, 4, dan 5 mm), garis pusat pic (10, 20, 40, dan 60 mm) dan nombor Reynolds (Re) dalam julat 5,000 hingga 20,000 dipertimbangkan. Kesan partikel nano CuO dan MgO yang tersebar dalam etilena glikol tulen (EG) sebagai cecair asas dengan garis pusat 40 nm dan kepekatan isipadu 0 hingga 5% pada aliran bendalir dan pemindahan haba disiasat sepanjang dinding saluran hulu diatur ke 200 mm dan panjang dinding hilir adalah 300 mm. Ketinggian alur masuk dan alur keluar masing-masing adalah 10 mm dan 20 mm. Nisbah pengembangan adalah 2. Hasilnya menunjukkan bahawa menggabungkan dinding beralun dengan langkah pandangan belakang dengan ketara meningkatkan pemindahan haba, disertai dengan kenaikan sedikit dalam faktor geseran. Dinding beralun trapezoid menunjukkan peningkatan tertinggi dalam kadar pemindahan haba pada ketinggian jerayun 4 mm dan garis pusat pic 20 mm. Menggabungkan saluran langkah pandangan belakang dengan dinding beralun meningkatkan nombor Nusselt hingga 62% pada Re = 5,000. Kriteria penilaian prestasi meningkat apabila ketinggian jerayun meningkat sehingga mencapai 4 mm dan kemudian menurun dengan curam.

Selain itu, hasil eksperimen menunjukkan bahawa pekali pemindahan haba meningkat apabila pecahan isipadu partikel nano meningkat. Berdalir nano CuO-EG meningkatkan bilangan Nusselt hingga 11% berbanding EG tulen pada pecahan

isipadu partikel nano sama dengan 0.05. Faktor geseran berdalir nano CuO meningkat hingga kira-kira 15% pada pecahan isipadu 0.01 dan 0,03 dan bilangan Reynolds 5,000 dan menurun ketika bilangan Reynolds meningkat. Nilai maksimum kriteria penilaian prestasi yang dicapai adalah 1.5 pada pecahan isipadu partikel nano sama dengan 0.03 untuk kes CuO sementara mencapai 1.2 untuk kes berdalir nano MgO.

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BFS	Backward-facing step
A	Area, m^2
AR	Aspect ratio
Er	Expansion ratio
C_p	Specific heat capacity, J/kgK
D_h	Hydraulic diameter, m
a	Amplitude height
p	Pitch diameter
DW	Distilled water
f	friction factor
FVM	Finite volume method
g	Gravitational acceleration, m/s^2
h	Convection heat transfer coefficient, W/m^2K
h	Inlet channel height, m
H	Outlet channel height, m
HTE	Heat transfer enhancement
I	Current, A
k	Thermal conductivity, W/mK
L, *l*	Length, m
Nu	Nusselt number
P.P	Pumping power, W
PEC	Performance evaluation criteria
Pr	Prandtl number
ΔP	Pressure difference, pa
q	Heat flux, W/m^2
Q	Heat flux, W
R	Radius, m
Re	Reynolds number
T	Temperature, K
t	Thickness, m

u	Velocity, m/s
V	Voltage, v
W	Weight, g

Greek symbols

β	Diffusivity
ρ	Density, kg/m^3
ϕ	Volume fraction
μ	Dynamic viscosity, kg/m.s
τ	Wall shear stress, pa

Subscripts

avr	average
b	bulk
bf	base fluid
eff	effective
f	fluid
m	mean
nf	nanofluid
np	nanoparticle
w	wall
x	local

CHAPTER 1

INTRODUCTION

1.1 Background

Heat transfer enhancement has significant attention in the last decades due to the critical role of heat transfer in saving power and increase efficiency in many engineering applications such as cooling systems, automobiles, and ventilation systems. In most of these applications, heat transfer is achieved through devices, for example, condensers, evaporators, heat exchangers, and heat sinks. The increases in the thermal efficiency of these devices are worthwhile, due to the ability to minimize these devices' size and to increase efficiency, which is desirable for application with compactness requirements.

The traditional techniques of improving the heat transfer, such as reducing the thermal boundary layer thickness or increasing the surface area, lead to an increase in the cost and mass of the heat transfer device. However, there are several effective techniques to enhance heat transfer. Some techniques are considering the thermal conductivity of working fluid or utilizing a vortex generator. Adding some amount of high thermal conductivity nanoparticles materials to a base fluid such as water, oil, and ethylene glycol increases the thermal conductivity of the base fluid. Suspension of the nanoparticle size material into a base fluid is known as nanofluid. Nanofluid is a new type of working fluid introduced by Choi and Eastman (1995). Generally, nanofluids can be the significant adjustable coolant in the world, as in various situations. Nanofluid can play the role of flexible cooling method because it can be designed to fulfil specific inquiries (Sadeghinezhad *et al.,* 2016; Sharma *et al.,* 2016).

Sudden expansions are widely used in different engineering applications, such as buildings, vehicles, electronic cooling, energy system, flow in combustors, heat exchangers, and many more. In general, the separation and reattachment phenomena of the flow in expansions led to a dramatic drag and pressure drop increment, and that yield a positive impact on heat transfer rate (Mohammed *et al.,* 2017a; Hilo *et al.,* 2018). Flow over a backward or forward-facing step is a benchmark problem where this phenomenon occurs and thus several computational and experimental works have been performed for flow over a backward and forward step Selimefendigil and Öztop (2017).

For a forward-facing flow, one or two recirculation regions may have formed adjacent to the step, depending on the magnitude of the Reynolds number of the flow and the thickness of the boundary layer of the momentum at the step. A separating region can develop downstream of the step, and another may develop upstream of the step. These separate flow regions make this geometry more difficult to analyse than the backward-facing step in which only one separate flow region exists behind the phase. Due to this fact, a very limited number of researchers focused on the forward-facing flow kherbeet *et al.* (2016).

In addition to its engineering interest, the simplicity of the backward-facing step (BFS) geometry makes it a suitable case of sudden expansions to study the fluid flow and heat transfer characteristics employing both simulation and experiments. The vast majority of the experimental studies such as (Armaly *et al.,* 1983; Driver and Seegmiller, 1985; Kasagi and Matsunaga, 1995) are focused on the reattachment length (X_r) depending on a single configuration of expansion ratio (*ER*) and Reynolds number (*Re*). By contrast, there are only a limited number of studies such as Abu-Mulaweh *et al.,* (1993) who investigated the effect of reattachment length on the heat transfer under laminar flow.

Recently, numerous studies have focus on inserting an obstacle in the backward-facing step channel to enhance the heat transfer such as (Kumar and Vengadesan, 2019). It was reported that oscillating fin is an effective method to enhance the heat transfer rate with minimum pressure drop. Mohammed *et al.,* (2019) add a different shape of blockage in the BFS channel. The result showed that the average Nusselt number in the case of trapezoidal blockage had increased by 32% compared with standard cases.

1.2 Heat transfer enhancement techniques

The need for high-performance heat exchangers has led researchers to develop heat transfer enhancement techniques. One of the common techniques involves decreasing thermal impedance by increasing the surface area of the heat exchanger or by minimizing the thickness of the thermal boundary layer on the heat exchanger surface. However, the increase in the surface area decreases the volume or mass of the heat transfer fluid and heat exchanger. The thermal boundary layer thickness is decreased by the formation of vortices. There are two types of heat transfer enhancement methods: (i) active and (ii) passive. Active methods require external power (e.g. surface and fluid vibration) and an electrostatic domain. Passive methods, on the other hand, do not require the use of external heat transfer capacity, and heat transfer is improved using extended surfaces (fins), vortex flow devices, rough surfaces, displaced promoters, and fluid additives (nanofluids). This research focuses on the combination of two passive methods (surface roughness and solid additives). **Figure** 1.1 presents a summary of the methods used to enhance heat transfer (Sidik *et al.,* 2017).

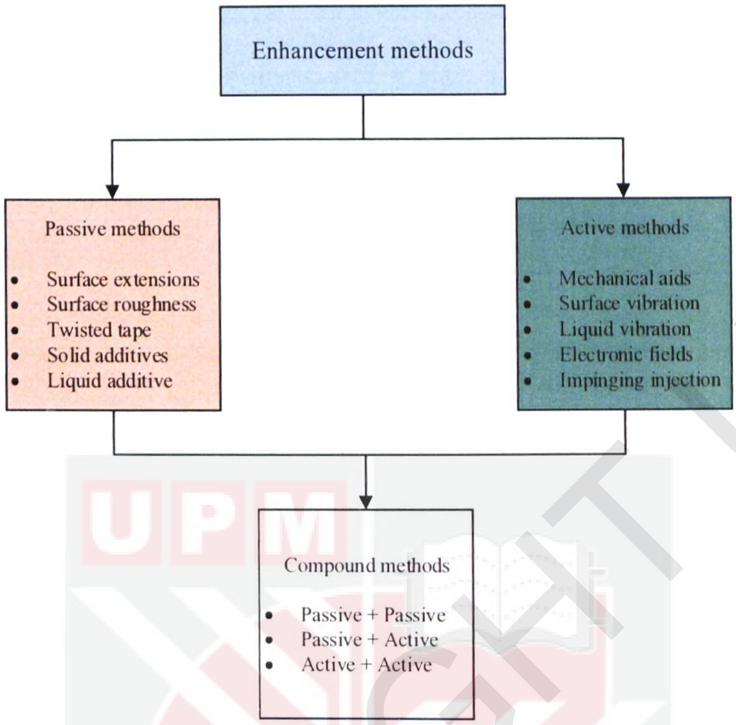

Figure 1.1 : Heat transfer enhancement methods (Sidik *et al.*, 2017)

1.3 Problem statement

Flow separation and reattachment phenomena have taken place in many thermal systems, and a lot of effort has been made over the last decade to understand the hydrodynamics and thermal implications of these phenomena. However, there is a lack of in-depth studies in this area, which are the motivation behind this research. In addition, nanofluid flows in backward-facing step channels under turbulent flow conditions (with flow separation) are typically excluded from the thermal analysis not only because of the complexity of these flows but also 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 flows in backward-facing step channel. Therefore, this study provides comprehensive data on these flows, which will assist thermal designers in designing heat exchangers with high thermal efficiency.

The corrugation wall has been used widely in different heat transfer devices such as heat exchanger to increase the compactness of the exchanger and in return increase the heat transfer surface area (Brien and Sparrow, 1982; Naphon, 2008; Mohammed *et al.*, 2017b; Ajeel, Salim and Hasnan, 2019). Some corrugated shape gives a higher heat transfer rate and lower pressure drop compared to others (Elshafei *et al.*, 2009; Mohammed *et al.*, 2013; Tokgoz *et al.*, 2017). The flow separation and reattachment region significantly affect the heat transfer due to the mixing of high and low fluid energy. In BFS geometry, the separation occurs at the sharp corner of the step causing a recirculation region behind the step. Meanwhile, when the flow passes over a corrugated wall a recirculation zone will occur in the diverging section of each corrugation. In order to take advantage of both techniques, Selimefendigil and Öztop (2017) have investigated the effect of a combined triangular corrugated wall with BFS channel on heat transfer and fluid flow. However, the effect of a combined different corrugated wall with BFS channel on heat transfer and fluid flow still required further study, since it doesn't fulfil the industry needs and the behavior of the flow is not entirely understood under these kinds of the channel.

Conventional liquids such as water, engine oil, glycerine, and ethylene glycol, play significant roles in various industrial applications, but due to the limitation of the thermal conductivity, many researchers have considered nanofluids as an alternative working. However, the behavior of nanofluid in terms of heat transfer rate and the penalty pressure drop does require further studies to cope with the industry requirement.

1.4 Objectives

The main objectives of the present research are:

1. To investigate the effects of combined different corrugations wall with BFS channels on fluid flow and heat transfer.
2. To determine the effect of corrugation parameters such as amplitude height and pitch diameter on fluid flow and heat transfer.
3. To examine the fluid flow and heat transfer characteristics of (CuO-EG and MgO-EG) nanofluids through the BFS channel.
4. To determine the effect of nanofluid volume concentration on the fluid flow and heat transfer.

1.5 Novelty of the research

The present research has derived an investigation on the effect of nanofluid fluid flow and heat transfer over a backward-facing step. A new experimental result of the ability to use CuO-EG and MgO-EG nanofluids as a working fluid in the BFS channel has been provided. The maximum value of the PEC reaches up to 1.5 for the case of CuO-EG nanofluids. The enhancement of heat transfer by combined the corrugated wall with the BFS channel reaches 62% and the PEC reached 1.4 compared to the original case of the BFS channel. Findings will be a useful reference to using nanofluids and corrugated walls in the various systems.

1.6 Research hypothesis

The present research implemented some assumptions and hypotheses as a guideline for the solution of the problem statement. The key assumptions in this work are that using nanofluids as a working fluid will increase the heat transfer rate in the backward-facing phase channel as the addition of CuO or MgO nanoparticles to the based fluid will enhance the thermal properties of the system, such as thermal conductivity. The BFS channel with corrugated downstream will enhance the heat transfer. The analysis will assume that adding a corrugated wall to the backward-facing step channel will generate more vortex and increase the Heat transfer rate with penalty increase of skin friction coefficient and pressure drop.

1.7 Research scope

The scopes and limitations of the present study in the range of objectives are stated as following;

1. Three wall corrugated shapes were considered, trapezoidal, triangular, and zigzag as different corrugated shapes provide different hydrodynamic flow. The corrugation parameter such as amplitude height is set at 1, 2, 3, 4, and 5 mm, and the pitch diameter is set at 10, 20, 40, and 60 mm.

2. The study considers the turbulent flow at Reynolds number range from 5,000 to 20,000. In the numerical section, the $k-\varepsilon$ turbulent model with RNG was selected, where it is suitable for the separation flow (Ahmad *et al.*, 2019) (Mohammed *et al.*, 2013).

3. In mathematical modeling, single-phase models were used to simulate the convective heat transfer of nanofluid flow in the BFS channel (Armaly *et al.*, 2003).

4. The effect of mass transport (change of phase, chemical reaction, transpiration, and mass dissipation, etc.) are neglected.

5. Two types of nanoparticles have been used including; CuO and MgO. The CuO nanoparticles have high thermal conductivity and the MgO have low cost and widely available. The thermal properties of the nanofluids such as thermal conductivity, viscosity, density, and specific heat for all nanofluids have been experimentally measured.

6. Water is used as a base fluid for all numerical studies, while both water and ethylene glycol were considered in the experimental study.

7. The research is carried out for an average nanoparticle diameter of 20 nm, volume concentration of 1, 3, and 5 % nanoparticles, and ethylene glycol as a based fluid.

1.8 Layout of the thesis

The thesis outlines are organized into six chapters in the following manner:

Chapter one presents a basic background and concepts, problem statement, the main objectives, and methodology of this research, and the novelty of the research. Chapter two provides a literature review that is divided into two sections. The first section deals with the fluid flow and heat transfer over the BFS channel and corrugated channel, including the numerical and experimental study. The second section express the role of nanofluid and its characteristic of heat transfer and fluid flow. Chapter three deals with the details of the numerical models, boundary condition, governing equation, and the validation of the code, as well as, the experimental setup used in this study, the test section assembling, the preparation of nonfluid, and the test procedure are presented in detail. Chapter four presents the numerical and experimental results which are discussed extensively here. Moreover, a comparison between the numerical and experimental data is provided with an explanation for the discrepancies and agreement. Finally, Chapter five presents the conclusion of the research and recommendations and suggestions for future work regarding the flow over the backward-facing step channel.

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APPENDICES

Appendix A

Uncertainty

Firstly, the error can be defined as following; the error of an indicated value is the difference between the indicated value and the true value of the quantity being measured. It is the quantity which algebraically subtracted from the indicated value gives true value.

The sources of measurement error may be equipment error, random error, or computational error. Equipment errors include inaccuracies due to calibration or checking a scale or reading of instrument conform to an accept standard. Random errors are caused by random, unpredictable variations in the measurement system and they can largely be eliminated by calculating the mean of measurement. While the computational errors result from an approximation of the decimal fractions to the less order such an approximation of the ($\pi = 3.1415927$) to ($\pi = 3.14$).

The uncertainties of quantities which are included in *Re* number are ρ, u_m, D_h, and μ. For *Nu* number, the x_i's are Q, D_h, k, T_w, and T_b. While for friction factor the quantities are D_h, ΔP, ρ, L, and u_m. The final formula for *Nu* number, *Re* number, and friction factor can be written as following respectively;

$$U_{Nu} = \left[\left(\frac{\partial Nu}{\partial I}U_I\right)^2 + \left(\frac{\partial Nu}{\partial V}U_V\right)^2 + \left(\frac{\partial Nu}{\partial D_h}U_{D_h}\right)^2 + \left(\frac{\partial Nu}{\partial A_w}U_{A_w}\right)^2 + \left(\frac{\partial Nu}{\partial k}U_k\right)^2 + \left(\frac{\partial Nu}{\partial T_w}U_{T_w}\right)^2 + \left(\frac{\partial Nu}{\partial T_b}U_{T_b}\right)^2\right]^{1/2} \quad \text{(A-1)}$$

$$U_{Re} = \left[\left(\frac{\partial Re}{\partial \rho}U_\rho\right)^2 + \left(\frac{\partial Re}{\partial u_m}U_{u_m}\right)^2 + \left(\frac{\partial Re}{\partial D_h}U_{D_h}\right)^2 + \left(\frac{\partial Nu}{\partial \mu}U_\mu\right)^2\right]^{1/2} \quad \text{(A-2)}$$

$$U_f = \left[\left(\frac{\partial f}{\partial D_h}U_{D_h}\right)^2 + \left(\frac{\partial f}{\partial \Delta P}U_{\Delta P}\right)^2 + \left(\frac{\partial f}{\partial \rho}U_\rho\right)^2 + \left(\frac{\partial f}{\partial L}U_L\right)^2 + \left(\frac{\partial f}{\partial u_m}U_{u_m}\right)^2\right]^{1/2} \quad \text{(A-3)}$$

BIODATA OF STUDENT

Ali Kareem Hilo was born in Missan, Iraq, on 25th July 1992. He received his Bachelor of Science in Mechanical Engineering degree from University of Technology, Iraq in 2014. He received his Master of Innovation and Engineering design degree in 2017 from Universiti Putra Malaysia, Malaysia. He embarked on his PhD research titled "**EXPERIMENTAL AND NUMERICAL STUDY OF NANOFLUID FLOW AND HEAT TRANSFER IN CORRUGATED BACKWARD-FACING STEP CHANNEL USING ETHYLENE GLYCOL AS BASED FLUID**" in Universiti Putra Malaysia in August 2017. He can be contacted at Ali.k.hilo92@gmail.com

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