UNIVERSITI PUTRA MALAYSIA

FORCED CONVECTION NANOFLUIDS THROUGH CORRUGATED BACKWARD FACING STEP CHANNELS USING NUMERICAL ANALYSIS

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By

KAFEL ABDULAZEEZ MOHAMMED

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

November 2017

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, Assoc. Prof. Ir. Dr. Abd Rahim Abu Talib, Assoc. Prof. Ir. Dr. Nuraini Abdul Aziz, and Assoc. Prof. Ir. Dr. Kamarul Arifin Ahmad, for their valuable guidance throughout this research. Lastly, I dedicate this thesis to 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

FORCED CONVECTION NANOFLUIDS THROUGH CORRUGATED BACKWARD FACING STEP CHANNELS USING NUMERICAL ANALYSIS

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November 2017

Chairman : Abd. Rahim Abu Talib, PhD, PE
Faculty : Engineering

Due to the importance of heat exchangers in various engineering applications, it is crucial to develop compact, lightweight heat exchangers with high thermal efficiency and low manufacturing cost. Much effort has been made to significantly enhance heat transfer and this can be achieved by designing corrugated walls for the heat exchanger channels. For this purpose, corrugated backward facing step wall is one of the many suitable techniques to enhance the heat transfer in heat exchangers. When fluid flows in a corrugated facing wall, the flow becomes disturbed due to growing re-circulation regions near the corrugated wall, which enhances the mixing of fluid as well as heat transfer. In this research, numerical modelling is carried out using ANSYS/FLUENT 15.0 software. The continuity, momentum and energy equations are discretized and solved using the finite volume method. The SIMPLE algorithm scheme is applied to link the pressure and velocity fields inside the domain. In the current work, the flow and heat transfer of nanofluids in corrugated facing channels are examined numerically. Five different types of nanofluids such as Al_2O_3, CuO, SiO_2, ZnO and Hamzel® silica aerogel-water with nanoparticle diameters in the range of 25 to 80 nm and the range of nanoparticle volume fraction from 0 to 4% are examined. The effects of geometrical parameters such as the amplitude height and wavelength of corrugated facing step channels in addition to the effect of Reynolds number on the flow and thermal fields are presented and analyzed. Comparisons of the numerical results with those available in the literature have been presented and a good agreement between the results is observed. The Reynolds number is varied between 100–1,500 and 5,000–20,000 for laminar and turbulent flows, respectively.

In general, the average Nusselt number and pressure drop increase with an increase in the amplitude height and nanoparticle concentration. However, there is a decrease in these parameters with an increase in the wavelength and nanoparticle diameter. The silicon dioxide-water nanofluid provides the best thermal hydraulic performance. The trapezoidal corrugated facing step channel provides the best thermal-hydraulic performance at an amplitude height of 4 mm, followed by the triangular corrugated facing step channel. The simulation results conform well with those in the literature.

Simulations are also conducted to examine the effect of nanoparticle concentration (0, 1, and 4%) and channel shape on the average Nusselt number and pressure drop for Hamzel® silica aerogel-water nanofluid in the laminar flow region. This novel nanofluid is a promising working fluid for heat exchangers due to its significant heat transfer enhancement when coupled with the trapezoidal corrugated facing step channel. This is indeed expected because of the high thermal conductivity and low density of this nanofluid.

The Nusselt number enhancement ratio reached to 80% and 85% when using Hamzel® silica aerogel-water in the trapezoidal-corrugate at Nanoparticle concentrations of 1% and 4% respectively. The trapezoidal-corrugate provides the highest thermal-hydraulic performance at amplitude height of 4mm and 2cm wavelength flowed by a triangle having the same property.

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

NANOBENDALIR PEROLAKAN PAKSA MELALUI SALURAN LANGKAH BERALUN MENGHADAP KE BELAKANG MENGGUNAKAN SIMULASI BERANGKA

Oleh

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Oleh kerana pentingnya penukar haba di dalam pelbagai aplikasi kejuruteraan, adalah mustahak untuk membangunkan penukar haba yang padat, ringan dengan kecekapan haba yang tinggi dan kos pembuatan yang rendah. Banyak usaha telah dibuat untuk meningkatkan pemindahan haba dengan ketara dan ini dapat dicapai dengan merekabentuk dinding beralun untuk saluran penukar haba. Untuk tujuan ini, suatu dinding langkah permukaan beralun merupakan salah satu daripada beberapa teknik yang sesuai untuk meningkatkan pemindahan haba dalam penukar haba. Apabila bendalir mengalir di dinding permukaan beralun, aliran itu akan terganggu kerana kawasan peredaran-semula yang semakin meningkat berhampiran dinding beralun, yang akan meningkatkan pencampuran bendalir serta pemindahan haba. Dalam kajian ini, pemodalan berangka dilakukan menggunakan perisian ANSYS/FLUENT. Kesinambungan, momentum dan persamaan tenaga didiskretkan dan diselesaikan dengan menggunakan kaedah isi padu terhingga. Skema algoritma SIMPLE digunakan untuk menghubungkan medan tekanan dan halaju dalam domain. Dalam kajian semasa ini, aliran dan pemindahan haba nanobendalir dalam saluran permukaan beralun diperiksa secara berangka. Lima jenis nanobendalir yakni Al_2O_3, CuO, SiO_2, ZnO dan aerogel silika Hamzel®-air dengan garis pusat nanozarah dalam lingkungan (25 , 40, 60, 80) nm dan pecahan isipadu nanozarah dari (0%, 1% 2%, 3%, 4%) diperiksa. Kesan parameter geometri seperti amplitud, ketinggian dan panjang gelombang saluran langkah permukaan beralun selain daripada kesan nombor Reynolds ke atas aliran dan medan haba dibentangkan dan dianalisis. Perbandingan keputusan berangka dengan yang terdapat di dalam literature telah dibentangkan dan persetujuan yang baik antara hasilnya diperhatikan. Nombor Reynolds dibeza-bezakan antara masing-masing 100-1,500 dan 5,000-20,000 untuk aliran lamina dan bergelora.

Secara umumnya, nombor purata Nusselt dan penurunan tekanan meningkat dengan peningkatan ketinggian amplitud dan kepekatan nanozarah. Walau bagaimanapun, terdapat penurunan parameter-parameter ini dengan peningkatan panjang gelombang dan garis pusat nanozarah. Nanobendalir silikon SiO2-air memberi prestasi hidraulik termal terbaik. Saluran langkah permukaan beralun berbentuk trapezium memberi prestasi termal-hidraulik terbaik pada ketinggian amplitud 4 mm, diikuti dengan saluran langkah permukaan beralun segi tiga. Keputusan simulasi mengikut dengan baikna keputusan yang ada di dalam literatur.

Simulasi juga dijalankan untuk mengkaji kesan kepekatan nanozarah (0, 1, dan 4%) dan bentuk saluran ke atas nombor purata Nusselt dan penurunan tekanan untuk nanobendalir aerogel silika Hamzel®-air di kawasan aliran lamina. Nanobendalir baru ini adalah bendalir bekerja yang membawa harapan untuk penukar haba disebabkan oleh peningkatan pemindahan haba yang ketara apabila digabung dengan saluran langkah permukaan beralun trapezium. Ini sememangnya disangkakan kerana kekonduksian termal yang tinggi dan ketumpatan rendah nanobendalir ini.

Nisbah peningkatan Nombor Nusselt mencapai 80% dan 85% apabila menggunakan silika aerogel Hamzel®-air di dalam trapezium-beralun dengan kepekatan nanozarah di paras 1% dan 4% masing-masing. Trapezium-beralun memberi prestasi terma-hidraulik tertinggi pada ketinggian amplitud 4 mm dan 2 cm panjang dialirkan oleh segi tiga yang mempunyai ciri yang sama.

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بسم الله الرحمن الرحيم

"مَن كَانَ يُرِيدُ الْعِزَّةَ فَلِلَّهِ الْعِزَّةُ جَمِيعًا ۚ إِلَيْهِ يَصْعَدُ الْكَلِمُ الطَّيِّبُ وَالْعَمَلُ الصَّالِحُ يَرْفَعُهُ ۚ وَالَّذِينَ يَمْكُرُونَ السَّيِّئَاتِ لَهُمْ عَذَابٌ شَدِيدٌ ۖ وَمَكْرُ أُولَٰئِكَ هُوَ يَبُورُ" (10) (فاطر)

"In the name of Allah, the Most Beneficient, the Most Merciful".
Blessings and peace be upon our beloved Prophet Muhammad S.A.W.

I wish to extend my warmest appreciation to everyone who have taken care of me, and for giving me their love, friendship, moral support, and advice. All praise be to Allah the Almighty for granting me the strength, courage, patience, and perseverance to overcome all of the obstacles that I faced throughout my PhD journey, and for giving me the willpower to finish my work at this level. I wish to express my sincere appreciation to the Chairman of my supervisory committee, Assoc. Prof. Ir. Dr. Abd Rahim Abu Talib, for his ongoing guidance and support to improve my research skills and writing skills. I am also greatly indebted to my co-supervisors, Assoc. Prof. ir. Dr. Nuraini Abdul Aziz and Assoc. Prof. Ir. Dr. Kamarul Arifin Ahmad for their insightful comments and for motivating throughout my research. None of this would have been possible without the contributions of everyone who matters. I also wish to express my deepest appreciation to my parents for their unconditional love and support, and for always encouraging me to do my best in all of my endeavours. I would like to express my deepest gratitude to my brothers and my family for their support during this work.

I certify that a Thesis Examination Committee has met on 20 November 2017 to conduct the final examination of Kafel Abdulazeez Mohammed on his thesis entitled "Forced Convection Nanofluids Through Corrugated Backward Facing Step Channels using Numerical Analysis" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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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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Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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Nam of Chairman of Supervisory Committee: Associate Professor Ir. Dr. Abd Rahim Abu Talib

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Name of Member of Supervisory Committee: Associate Professor Ir. Dr.Nuraini Abdul Aziz

Signature: ____________________________________
Name of Member of Supervisory Committee: Associate Professor Ir. Dr.Kamarul Arifin Ahmad

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LIST OF ABBREVIATIONS

Al_2O_3	Aluminium oxide
BFS	Backward-Facing Step
CFD	Computational Fluid Dynamics
CuO	Copper oxide
EG	Ethylene Glycol
FFS	Forward-Facing Step
FVM	Finite Volume Method
SiO_2	Silicon dioxide
S/H	The ratio of step length to the height of channel
ZnO	Zinc oxide

Greek Characters

C_p	specific heat, J/ kg.K
D_h	hydraulic diameter, m
dp	Nanoparticles diameter, nm
g	gravitational acceleration, m/s^2
Gr	Grashof number, $g\beta q_w s^4/(kv^2)$
H	total channel height, m
h	convective heat transfer coefficient, $W/m^2{\cdot}K$
h	inlet channel height, m
k	thermal conductivity, W/m.K
$\dot{m}$	Mass flow rate (kg/s)
Nu	Nusselt number, $h.D_h/k$
P	dimensionless pressure, $P = (p+\rho gx)/\rho\ u_\infty^2$
Pr	Prandtl number, v_f/α_f
q	heat flux, W/m^2
Re	Reynolds number, $\rho u_\infty D_h / \mu_f$
s	step height, m
T	fluid temperature, K
T_∞	temperature at the inlet or top wall, K
T_w	temperature of the heated wall, K

u	velocity component in x-direction, m/s
u_i	local inlet velocity, m/s
u_∞	average velocity for inlet flow, m/s
U	dimensionless streamwise velocity component, u / u_∞
v	velocity component in y-direction, m/s
V	dimensionless transverse velocity component, v / u_∞
VG	Vortex generator
W	channel width, m
X	dimensionless streamwise coordinate, x/s
Xi	upstream length, m
Xe	Streamwise coordinate as measured from the step, m
Xr	reattachment length, m
Y	dimensionless spanwise coordinate, y/s
Z	dimensionless transverse coordinate, z/s
φ	nanoparticles concentration
α_f	thermal diffusion of fluid, $N.s/m^2$
β	thermal expansion coefficient, 1/K
θ	dimensionless temperature,
ρ_f	density of fluid, kg/m^3
ρ_s	density of solid, kg/m^3
ν_f	kinematic viscosity of fluid, m^2/s
μ	dynamic viscosity, $N.s/m^2$
ε	Dissipation per unit mass
г	Diffusion coefficient

Subscripts

eff	effective
f	fluid
s	solid
nf	nanofluid
w	wall
∞	inlet condition

CHAPTER 1

INTRODUCTION

1.1 Background

Studies on heat transfer enhancement of heat exchangers have received much attention in recent years since it is imperative to design heat exchangers with high thermal efficiency. Knowledge on heat transfer enhancement is essential in order to develop compact, lightweight heat exchangers with high thermal efficiency and low manufacturing cost. Nanofluids have garnered much attention in recent years for use as coolants in various industrial applications. This new class of heat transfer fluids contain pendent nanoparticles with high suspension stability compared with fluids in which the particles are within the millimetre or micrometre range (Fuskele, V., & Sarviya, R. M. 2017). Heat transfer fluids such as water, ethylene glycol, glycerine, and engine oil play an important role in many industrial applications. Many studies have been published regarding heat transfer and fluid flow of flows through channels with facing steps (Mohammed *et al.*, 2017). The effects of boundary conditions, fluid type, and geometry on heat transfer enhancement have been investigated. Researchers have also developed ways to improve the accuracy of numerical predictions for convective heat transfer and fluid flow characteristics of flows in facing step channels (Heshmati *et al.*, 2014). These data are vital for industrial heating and cooling applications where flows through channels with sudden expansion or contraction are common. In this regard, numerical and experimental studies have been carried out over the years for laminar and turbulent flows. Studies have shown that using nanofluids in corrugated channels enhances heat transfer with a slight pressure drop. The heat transfer enhancement potential of these fluids in corrugated channels enable engineers to develop highly effective and compact heat transfer exchangers to suit a variety of industrial applications such as transportation, electronic cooling systems, chemical processes, combustion chambers, turbine blade cooling, environmental control systems, and high-performance heat exchangers. Figure 1.1 shows the various types of plate-fin heat exchangers (Webb, 1984).

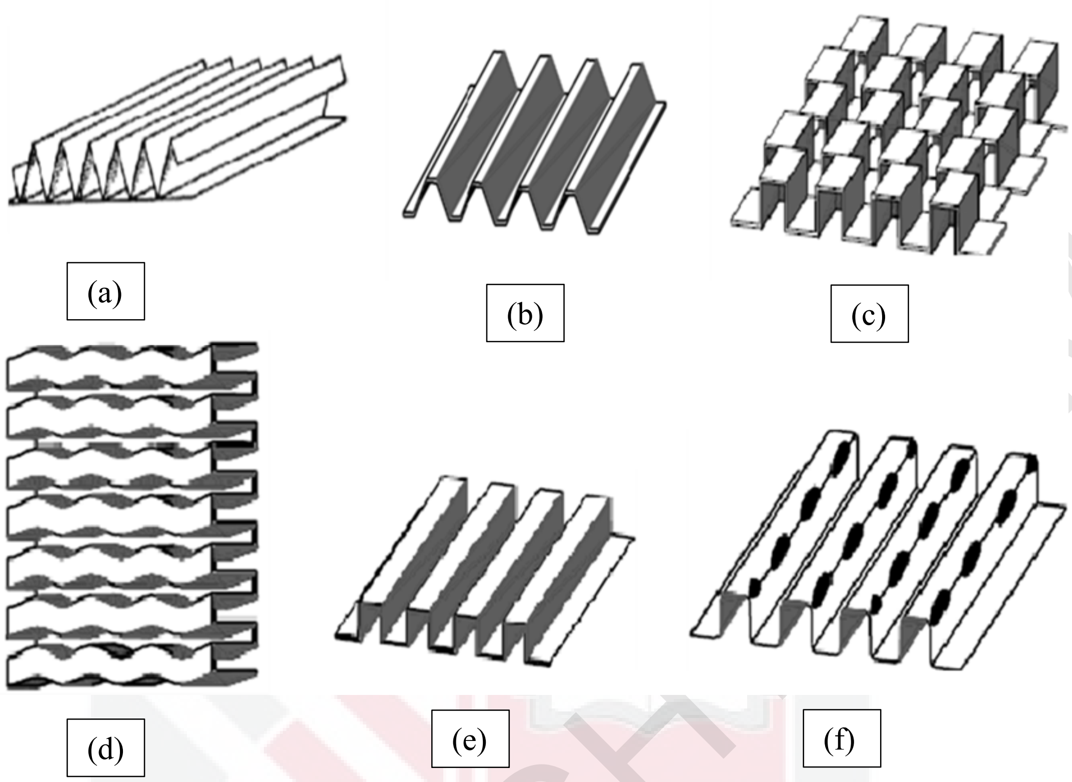

Figure 1.1 : Various types of plate-fin heat exchangers: (a) plain triangular fins, (b) plain trapezoidal fins, (c) offset strip fins, (d) wavy fins, (e) rectangular fins, and (f) perforated fins (Webb, 1984)

Owing to the escalating energy demands in the last few decades, much effort has been made to study and improve the thermal performance of heat exchangers. Improving the thermal performance by means of corrugated facing step channels is insufficient to fulfil industrial requirements. Nanofluids have attracted much attention because of their great potential as coolants in various heat transfer systems. This modern class of heat transfer fluids consists of pendant nanoparticles with high suspension stability compared with fluids containing micrometre and millimetre-sized particles. Heat transfer fluids such as ethylene glycol, water, glycerine, and engine oil play a vital role in various industrial applications. Much effort has also been made to develop compact and lightweight heat exchangers with high thermal efficiency and low manufacturing cost.

1.2 Heat transfer enhancement techniques

The need for high-performance heat exchangers has driven researchers to improve heat transfer enhancement techniques. One of the conventional techniques involves reducing the thermal impedance by increasing the heat exchanger surface area or decreasing the thermal boundary layer thickness on the heat exchanger surface. However, increasing the surface area increases the volume or mass of the heat transfer fluid and heat exchanger. The thermal boundary layer thickness is reduced by generating vortices. There are two types of heat transfer enhancement techniques: (1) active and (2) passive. Active techniques require an external power (*e.g.* surface and fluid vibrations) and an electrostatic domain. In contrast, passive techniques do not require the application of external power for heat transfer enhancement, and heat transfer is enhanced by using a rough surface, extended surfaces (fins), displaced promoters, vortex flow devices, and fluid additives (nanofluids). This research is focused on integrating two passive techniques in order to enhance heat transfer of heat exchangers. Figure 1.2 shows a summary of the techniques used for heat transfer enhancement (Sidik, N. et al., 2017).

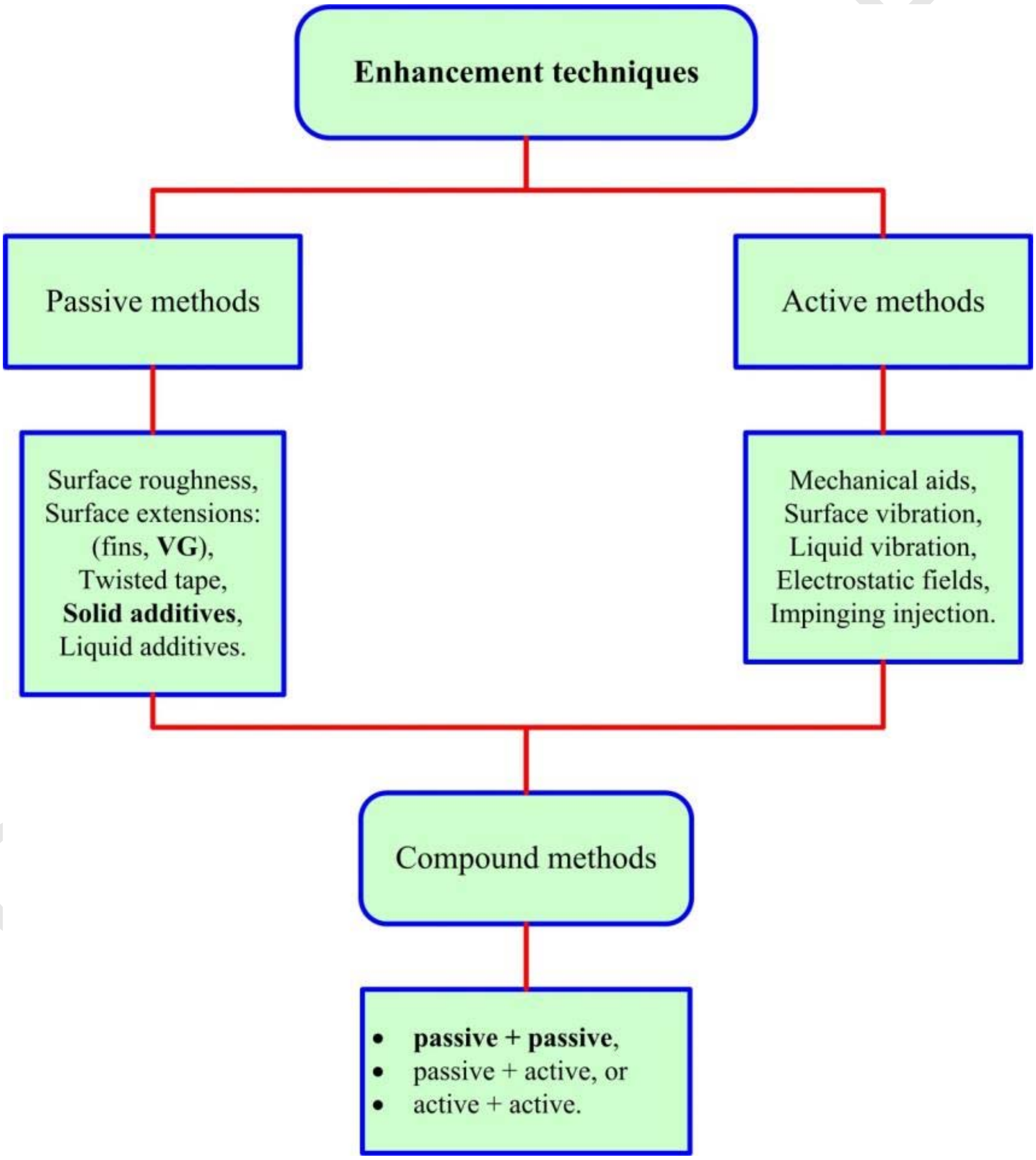

Figure 1.2 : Summary of heat transfer enhancement techniques (Sidik, N. 2017).

Vortex generators such as fins, ribs, and wings fixed onto the heat transfer surface have been successfully used to enhance heating or cooling in thermal systems such as gas turbines, heat exchangers, and electronic devices. These vortex generators serve as obstacles that generate three-dimensional swirl flow and secondary vortices which disturbs the growth of the viscous sub-layer and increase the rate of heat transfer. The need for non-circular ducts (*e.g.* trapezoidal and triangular ducts) with low pressure drop (Edalati *et al.*, 2016) has motivated researchers to use fluids with high thermal conductivities such as nanofluids in order to increase the thermal performance of these ducts.

1.3 Research motivation

Flow separation and reattachment phenomena take place in many thermal systems and much effort has been made in the last decade to understand the hydrodynamics and thermal aspects of these phenomena. However, there is a lack of in-depth studies in this area, which forms the motivation of this research. Furthermore, nanofluid flows in corrugated facing step channels in turbulent flow conditions (with flow separation) are typically excluded from thermal analysis not only because of the complexity of these flows, but also due to the high computational and experimental resources required to study the problem. To date, there is a lack of in-depth studies concerning nanofluid flows in corrugated facing step channels. Hence, this research provides comprehensive data on these flows which will assist thermal designers in designing heat exchangers with high thermal efficiency, in which nanofluids are used as the working fluids.

1.4 Problem statement

Owing to the escalating energy demands in the last few decades, much effort has been made to study and improve the thermal performance of heat exchangers. However, improving thermal performance by means of corrugated backward facing step channels is not sufficient to fulfil all industrial requirements.

Nanofluids have attracted much attention because of their great potential as coolants in various industrial applications. This modern class of heat transfer fluids consists of pendant nanoparticles with superior suspension stability compared with fluids containing particles within the micrometre or millimetre range. Heat transfer fluids such as ethylene glycol, water, glycerine, and engine oil play a vital role in industrial applications, and there is a critical need to develop compact and lightweight heat exchangers with high thermal efficiency and low manufacturing cost.

Currently, there is no perfect heat exchanger. More work need to be done to enhance the heat transfer. Enhancement techniques using facing step geometry (26%), surface roughness (35%), and liquid additive (5%). Combination of the above techniques surface roughness + liquid additive (40%), while facing step geometry + liquid additive (31%). For all of these enhancement techniques the industry still feel that is not enough and we are looking for more than 50% enhancement.

1.4.1 Proposed New Channel Design

Figure 1.3. Present the new Proposed of triangle and trapezoidal wall compound with facing-step geometry, the length of wave is (Lw) and the amplitude height is (a). Note the step height is kept constant

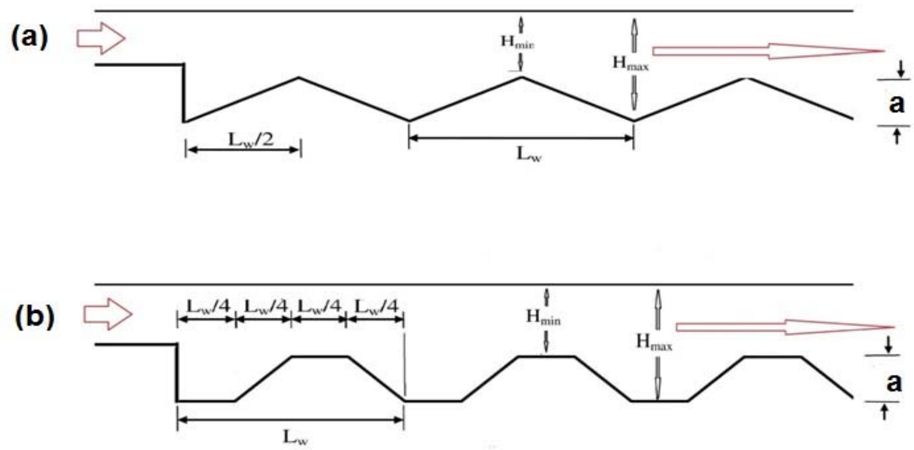

Figure 1.3 : Corrugated backward facing step channels

1.5 Research hypotheses

To carry out research work associated with the problem statement and objective, some assumption and research hypothesis will be formulated as a guideline. Basic assumptions that will be adapted in this work are that the corrugated facing step channels will enhance heat transfer. The analysis will assume the corrugated facing step channels will increase pressure drop and skin friction coefficient and Nanofluids will enhance heat transfer in corrugated facing step channels.

1.6 Aim of the work

This study aims to study the double effect of combined the corrugated wall and different type of nanofluids in back ward facing step channel in the heat transfer enhancement and answer the following questions :

a. What is the best geometry, amplitude height and wavelength for the triangular and trapezoidal corrugated facing step channels?

b. Which amplitude height and wavelength gives the best thermal hydraulic performance for the triangular and trapezoidal corrugated facing step channels?
c. Which nanofluid gives the best thermal hydraulic performance?
d. What is the ideal nanoparticle diameter?
e. What happens when the nanoparticle concentration is increased?
f. Which flow (laminar or turbulent) results in significant heat transfer enhancement?
g. Which flow (laminar or turbulent) results in a significant increase in the pressure drop?
h. Based on the performance evaluation criteria, is the combination of corrugated wall and nanofluids in triangular and trapezoidal corrugated facing step channels more than unity?

1.7 Research objectives

The main objectives of this research are set as follows in order to verify the hypotheses proposed in this research:

- To develop numerical models of corrugated facing step channels.
- To validate present study result with numerical and experimental result available in literature.
- To analyse the convective heat transfer, pressure drop, and skin friction coefficient of flows in corrugated facing step channels in laminar and turbulent flow conditions.
- To investigate the effect of different nanofluids and corrugated facing step channels on heat transfer enhancement.

1.8 Scope of research

The design of the plate heat exchangers is highly required to find the optimal structure of these devices. Currently, the flow and heat transfer characteristics of nanofluids in corrugated backward facing step channels are numerically investigated. Therefore, the scope of the current study is as follows:

1. The amplitude height of the VG is set at 1, 2, 3, and 4 mm with respect to the axial flow to keep the research in the domain of backward facing step.
2. In the mathematical modeling, the Low Reynolds number k-ε model of Launder and Sharma (1974) 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 flow in corrugated backward facing step channel (Armaly *et al.*, 2003).

4. The effect of mass transfer (by means of chemical reactions, phase changes, mass dissipation, transpiration, etc.) are neglected and only energy transfer by means of convective heat transfer is considered (Kays *et al.*, 1984).
5. Thermophysical properties such as thermal conductivity, diffusivity and specific heat for three types of silica aerogel Nano-powders have been experimentally measured.
6. Fourteen VG geometries (triangular and trapezoidal) are examined, whereby the amplitude height is set at 1, 2, 3, and 4 mm and the wavelength is set at 2, 4, 5, and 10 cm.
7. Water is used as the base working fluid Tzeng *et al.,* (2007).
8. Five types of nanofluids are studied: Al_2O_3-water, SiO_2-water, ZnO-water, and CuO-water nanofluids in addition to novel nanofluid (Hamzel® silica aerogel-water), which has never been used before in heat transfer studies.
9. The research is carried out for four nanoparticle concentrations: 1, 2, 3, and 4%.(Heshmati, 2014)
10. The research is conducted for four nanoparticle diameters: 25, 40, 60, and 80 nm. (Heshmati, 2014)
11. The Reynolds number (Re) is varied from 100 to 1,500 for laminar flow and from 5,000 to 20,000 for turbulent flow Ahmed et al. (2015).

1.9 Novelty of the research

To the best of the author's knowledge, there are no reported studies to date regarding the effect of nanofluids and corrugated backward facing step wall on heat transfer enhancement, and this research fulfils this gap in the existing body of knowledge. In addition, there are no studies on the effect of constant and variable properties on the Nusselt number, pressure drop, and skin friction coefficient. Furthermore, a numerical study is carried out on a novel nanofluid (Hamzel® silica aerogel-water nanofluid), which has never been used before in heat transfer studies.

1.10 Layout of the thesis

The chapters of this thesis are organized as the following manner: Chapter 2 provides an extensive review of literatures in the field of heat transfer enhancement using vortex generators and nanofluids and their applications. The advantages, disadvantages, problems and challenges of nanofluids are also presented. Chapter 3 includes the details of the problem domain, mesh generation and independency test of the mesh, validity of the code, boundary conditions, governing equations and method of solution used to obtain the numerical simulation. Testing of discretization scheme is also presented in this chapter. Chapter 4 presents the details of numerical results which are discussed thoroughly here. Finally, Chapter 5 contains the conclusion and recommendations for future works.

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