HEAT TRANSFER ENHANCEMENT IN HELICAL MICRO TUBE HEAT EXCHANGER USING COMPOUND TECHNIQUE

ADNAN HAMEED RASHEED

UNIVERSITI TEKNOLOGI MALAYSIA

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ADNAN HAMEED RASHEED

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ABSTRACT

The performance of heat exchangers can be altered to perform specific heat-transfer tasks via heat transfer augmentation techniques. These techniques can be divided into two groups that are active and passive. This study involved numerical and experimental investigation of heat transfer enhancement for laminar convective flow using a new type of tube insert, namely a helical microcoil in a heat exchanger with nanofluid. The research used microtube with 1.5 mm diameter, and three types of helical coil, namely circle, oval and elliptical with different diameters and pitches ((10 mm, 14 mm, and 18 mm Different types of nanofluids, Al_2O_3, CuO, SiO_2 and ZnO, were used as work fluids with different nanoparticle diameters (25, 50 and 75 nm) and different volume fractions (1%, 1.5%, and 2%). Water was used as the base fluid. The investigation covered Reynolds number in the range of 200 to 1800. Based on numerical simulation results, for all helical microcoil configurations and different types of nanofluids, experimental work was then developed to determine the optimum geometrical structures and parameters, empirical correlations of Nusselt Number and to formulate the frictional factor. A computational model using the ANSYS-FLUENT 18.0 was developed and evaluated against the experimental findings. It showed that helical microtube curvature swirls were an essential phenomenon to increase heat transfer. It also showed that the heat transfer and friction loss increased as volume fractions of nanofluids and Reynolds number increased while nanoparticle diameter decreased. The numerical and experimental results were compared, where the results showed a good agreement for different parameters. The conclusion is that compared to the straight coil, the helical microtube employment resulted in a clear augmentation in heat transfer with a certain increase in pressure drop. The highest value of the average Nusselt number ratio was 1.35 at Re = 1800 for circle shape with water as coolant. The maximum enhancement in heat transfer using nanofluids was around 11% compared to traditional fluid (water). The best thermal performance factor was 3.15, which was achieved using Al_2O_3 nanofluid with a volume fraction of 2% at pitch and diameter of 18 mm, and the Reynolds number was 1800.

ABSTRAK

Perlakuan sesebuah penukar haba dapat diubah untuk melakukan tugas pemindahan haba tertentu melalui teknik augmentasi pemindahan haba. Teknik-teknik ini boleh dibahagikan kepada dua kumpulan iaitu aktif dan pasif. Kajian ini melibatkan penyelidikan berangka dan ujikaji mengenai peningkatan pemindahan haba aliran perolakan lamina menggunakan sejenis sisipan tiub yang baharu, iaitu gegelung mikro heliks dalam penukar haba digabungkan bersama bendalirnano. kajian ini menggunakan tiubmikro berdiameter 1.5 mm, dan 3 jenis gegelung tiubmikro heliks, iaitu bulat, bujur dan elips dengan diameter dan nisbah heliks yang berbeza (10 mm, 14 mm, dan 18 mm). Bendalirnano yang berbeza, Al_2O_3, CuO, SiO_2 dan ZnO dengan diameter nanopartikel (25, 50, dan 75 nm), serta pecahan isipadu yang berbeza (1%, 1.5%, dan 2%) telah digunakan dalam kajian. Air telah digunakan sebagai cecair asas. Penyelidikan ini merangkumi nombor Reynolds dalam julat 200 hingga 1800. Berdasarkan kepada hasil simulasi berangka, bagi semua konfigurasi gegelung mikro heliks dan pelbagai jenis bendalirnano, kajian eksperimen dibangunkan untuk menentukan struktur dan parameter geometri yang optimum, hubungan empirik nombor Nusselt dan untuk merumuskan faktor geseran. Satu model komputeran menggunakan perisian ANSYS-FLUENT 18.0 dibangunkan dan dinilai berbanding dengan hasil penemuan eksperimen. Ia menunjukkan bahawa pusaran lengkungan tiub mikro heliks adalah satu fenomena penting untuk meningkatkan pemindahan haba. Ini juga menunjukkan bahawa pemindahan haba dan kehilangan geseran meningkat apabila pecahan isi padu bendalirnano serta Nombor Reynolds meningkat, manakala diameter nanopartikel menurun. Dapatan dari kajian berangka dan eksperimen telah dibandingkan, di mana hasilnya menunjukkan persetujuan yang baik pada parameter yang berbeza. Kesimpulannya adalah bahawa jika dibandingkan dengan gegelung lurus, penggunaan tiub mikro heliks menghasilkan peningkatan yang jelas dalam pemindahan haba dengan peningkatan kejatuhan tekanan tertentu. Nilai tertinggi dari nisbah nombor Nusselt secara purata ialah 1.35 pada Re = 1800 untuk bentuk bulatan dengan air sebagai penyejuk. Peningkatan maksimum dalam pemindahan haba menggunakan bendalirnano adalah sekitar 11% berbanding cecair tradisional (air). Faktor prestasi terma terbaik sebanyak 3.15 dicapai dengan menggunakan bendalirnano Al_2O_3 dengan pecahan isipadu sebanyak 2% pada nisbah heliks dan diameter sebesar 18 mm, dan nombor Reynolds adalah pada 1800.

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LIST OF ABBREVIATIONS

CFD	-	Computational fluid dynamics
CMC	-	Carboxy methyl cellulose
CNT	-	Carbon nanotube
DI	-	Deionized water
DLS	-	Dynamic light scattering
EDX	-	Energy dispersive x-ray analysis
FESEM	-	Field emission scanning electron microscopy
HCT	-	Helical coil tube
MC	-	Microchannel
MT	-	Microtube
MWCNT	-	Multi walled carbon nanotube
PANI	-	Polyaniline
PBCS	-	Pressure-based coupled solve
PEC	-	Thermal performance factor
SEM	-	Scanning electronic macroscopic
TEM	-	Transmission electron microscope

LIST OF SYMBOLS

A	-	Heat transfer surface area, (m^2)
C_p	-	Specific heat capacity, (J/kg K)
D_i	-	Tube inner diameter, (m)
D_h	-	Tube hydraulic diameter, (m)
D_o	-	Tube outer diameter, (m)
d_p	-	Nanoparticle diameter, (m)
d_f	-	Fluid molecule diameter, (m)
f	-	Friction factor
h	-	Heat transfer coefficient, (W/m^2. K)
K	-	Thermal conductivity, (W/m. K)
K_B	-	Boltzmann constant (J/K)
L	-	Tube length, (m)
D_c	-	Coil diameter
P_c	-	Coil pitch
m	-	Mass flow rate, (kg/s)
M	-	Molecular weight of the base fluid
N	-	Avogadro Number
Nu	-	Nusselt Number (dimensionless)
P	-	Pressure (Pa)
Δp	-	Pressure loss, (Pa)
Pr	-	Prandtl Number (dimensionless)
q	-	Heat transfer rate, (W)
q''	-	Heat flux (W/m^2)
Re	-	Reynolds Number (dimensionless)
T	-	Temperature (Celsius, Kelvin)
T_0	-	Reference temperature
u	-	Velocity (m/s)
ρ	-	Density (kg/m^3)
μ	-	Dynamic viscosity (kg/m^3)
ν	-	Kinematic viscosity (m^2/s)

α	-	Thermal diffusivity (mm^2/s)
η	-	Thermal performance factor (dimensionless)
ϕ	-	Volumetric concentration (%)

LIST OF SUBSCRIPTS

avg	-	Average
B	-	Brownian
bf	-	Base fluid
c	-	Cold
D	-	Darcy
eff	-	Effective
f	-	Fluid
fr	-	Freezing point
in	-	Inlet temperature
h	-	Hot
np	-	Nanoparticle
P	-	Particle
Out	-	Outlet temperature
Si	-	Inner surface
So	-	Outer surface

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Heat transfer enhancement is referred to techniques that revolve around improving the thermal performance of heat transfer systems. The improvements that occur due to these techniques reduce the size and capital cost of heat transfer systems. Heat transfer enhancement techniques have been developed and applied in many applications such as transportations, air-conditioning systems, cooling systems, nuclear reactors, cooling of electronic parts, applications used in space and aviation, optical and biomedical applications (Gugulothu *et al.*, 2017).

The classification for these enhancement techniques is divided into two main categories which are active and passive techniques. The active technique requires external power such as electric fields, jet impingement, acoustic or surface vibration. The passive technique does not require external power; examples include treated surfaces, rough surfaces, extended surfaces, coiled tubes, fluid additives (Nanofluids) and special surface geometries to the flow channel by incorporating inserts. Two or more passive and/or active techniques in the context of the compound technique may be used to produce an enhancement higher than each technique operating individually (Yilmaz *et al.*, 2003; Sheikholeslami and Ganji, 2015; Vashistha and Kumar; 2016, Omidi and Jafari, 2017; Alam and Kim, 2018).

Nowadays, micro-electronic cooling techniques, the characteristics of fluids flow and heat transfer in microtubes and microchannels have received a growing interest to improve the thermal treatment in relevant technologies. Microtubes are used in shell and tube heat exchanger which is gaining attention in transportation, biomedical, automobile industries and space applications such as gas turbines (Nacke *et al.*, 2011), integrated circuits (Qian and Wang, 2012), micro-reactors (Šalić *et al.*, 2012). Therefore, the design stage of the microthermal devices' and the enhancement of heat transfer coefficient of conventional fluids the main issue and challenge in developing energy-efficient heat transfer equipment's. The heat transfer rate can be improved by introducing a disturbance in the fluid flow (breaking the viscous and thermal boundary layers), but in the process pumping power may increase significantly and ultimately the pumping cost becomes high. Therefore, to achieve a desired heat transfer rate in an existing heat exchanger at an economic pumping power, there are several techniques used to improve the thermal performance of heat transfer equipment's. In this respect, manipulating the path of the main fluid by using helical microtube is one of the best important strategies (enhancement passive technique) to improve heat transfer. This technique lead to relatively more compact heat exchangers and allows cause secondary flow vortexes which promote higher heat transfer coefficients in single phase flows as well as in most regions of boiling by improves the fluid mixing and achieves the desired goal of improvement (Bejan *et al*., 2003). In addition liquid additives (nanofluids) exhibit enhanced thermal properties and convective heat transfer coefficients compared to conventional fluids such as water ethylene glycol and oil engine (Das *et al*., 2003). Suspension of nanoparticles improved the fluid thermal conductivity which consequently enhanced heat transfer performance.

This new type of helical microtube can present a new breakthrough in the heat transfer performance against the common smooth micro tube. The outcome of the present study not only will advance the development of high efficiency heat exchangers and design more compact heat exchanger with a view to minimize the overall volume and cost of heat exchanger thus decrease the pumping power required for a given heat transfer process.

1.2 Background of Study

The characteristics of fluids flow and heat transfer in microtubes and microchannels have attracted much attention of researchers because of the rapid developments of microelectromechanical systems (MEMS). These developments have great impacts on the microelectronic cooling techniques, the microheat exchanger, bioengineering, human genome project, medicine engineering, etc. It is evident that the understanding of the microscale phenomena is very important for designing efficient microdevices.

Several research studies have been implemented experimentally and numerically on heat transfer enhancement using different types of nanofluids under turbulent flow conditions. Xuan and Li (2003) investigated the turbulent flow convective heat transfer via an experiment in a uniform heat flux tube using Cu nanofluid with volume fraction of (0-2) %. The heat transfer coefficient was increased remarkably with Reynolds Number for all types of fluid tested. The Nusselt Number of nanofluid enhanced with volume fraction of nanoparticles is improved better than the base fluid under the same Reynolds Number. Maïga *et al*. (2006) have implemented a numerical investigation on the hydrodynamic and thermal behaviors of turbulent flow of saturated water and Al_2O_3 nanoparticles at various concentrations, flowing in a uniform wall heat flux boundary condition. They found that increasing particles volume fraction into the base fluid has increased the heat transfer coefficient, and a drastic effect has been induced on the wall's shear stress when in presence of nanoparticles. Bahremand *et al.* (2015) in the present study, turbulent flow in helically coiled tubes under constant wall heat flux is numerically and experimentally investigated. Pressure drop and convective heat transfer behavior of water and water–silver nanofluid are studied It was found that the utilization of the base fluid in helical pipe with greater curvature ratio compared to the use of nanofluid in straight tubes increased heat transfer more effectively. Rakhsha *et al*. (2015) steady state turbulent forced convection developing flow of a CuO nano-fluid inside helically coiled tubes at constant wall surface temperature was investigated both numerically and experimentally the applied CuO nano-fluid over pure water,The numerical results respectively demonstrate 6–7% and 9–10%

increase in the convective heat transfer and pressure drop of the applied CuO nano-fluid over pure water. Korpyś *et al*. (2020) this work presents experimental and CFD simulation results of heat transfer for water and CuO water nanofluid flow systems stabilized by capping agents. The experiments were carried out in a helically coiled tube in the range of turbulent flow regime with Reynolds numbers from 6000 to 21968, for practical applications importance.Nusselt number enhancement with regard to host liquid was observed, up to 18-35% for nanofluids under investigation. in othor words, addition of nanoparticles causes increase in the heat transfer coefficient of the nanofluid compared with the base liquid (water) up to 18 - 35%.

In addition, the effect of flow pulsation when in regards to heat transfer enhancement has been studied experimentally and numerically by numerous researchers. Xiao *et al.* (2009) investigated numerically the effects of gas flow in microtube. The second-order slip flow and temperature jump boundary conditions were applied to solve the momentum and energy equations in MT for an iso flux thermal boundary condition, which means that the heat flux at the boundary is fixed. The results indicated that the heat transfer effects associated with the rarefied flow were reduced for the second-order model. Nusselt Number was increased relative to the values of no-slip when the temperature jump effect was small. Koo and Kleinstreuer (2004) investigated experimentally the effects of viscous dissipation on the temperature field and the friction factor in a microtube (MT) and microchannel (MC). Three working fluids were used, water, methanol and iso-propanol. The results indicated that the viscous dissipation effect on the friction factor was increased as the system size decreased. For water flow in a tube with $D < 50$ μm, viscous dissipation becomes significant. For liquids, the viscous dissipation effects decreased as the fluid temperature increased. Aziz and Niedbalski (2011) used a form of numerical experimentation in order to investigate first and second order slip flow effects on the thermal development of dilute gas flow in a micro-tube with axial conduction and viscous dissipation. Following the results reported particularly for the second order slip model, the analytical solution predicts a higher velocity in the central region of the flow, but this pattern does not hold the same when it comes to the wall region, which is in fact reversed. The Nusselt Number local to the experiment was also decreased as the cooled section of the tube would carry the fluid.

According to the above literature, showed that the presence of the coil tube leads to promote heat transfer coefficients. Whereas the presence of nanofluid improves the effective thermal conductivity, leading to a significant increase in the convection heat transfer coefficient. Thus, the attractive characteristics of nanofluid with helical tube heat exchangers as well as the benefits and application of microtubes and microchannels have encouraged the current research to propose a combination of all three of this element into a single method which encompasses all of the benefits as well as extra ones that are carried on depending on the case that is being tested. This can provide even more improvement when compared to the individual use of micro coil with nanofluid or microtubes and microchannels (MT/MC) with nanofluid flow. the combination of nanofluid with the new configuration for the micro coil tube could be result in a higher degree of performance than the other forms of conventional liquids such as water, engine oil and ethylene glycol.

1.3 Statement of the Problem

Heat transfer enhancement techniques play a vital role in laminar flow since the heat transfer coefficient is generally low in plain microtubes. Active and passive techniques have been applied to improve heat transfer rates in a wide variety of products, which includes tube inserts, duct geometry modifications and drag coefficient reducer using some liquid additives. Tube inserts include helical microtube inserts, are perhaps the most convenient enhancement passive technique devices owing to their better thermal-hydraulic performance in laminar flow heat transfer by produce secondary flow vortexes which promote higher heat transfer coefficients in single phase flows as well as in most regions of boiling by improves the fluid mixing and achieves the desired goal of improvement (Bejan *et al.*, 2003). In addition, more compact heat exchangers, easy to fabricate, easy to fit and remove in existing heat exchangers.

Thermal conductivity of the heat transfer fluid is an important factor in efficiency energy heat transfer equipment. Fluids such as water, oil or even ethylene glycol are conventional fluids considered to have poor and limitation of the thermophysical properties, have always been the primary limitation in the development of energy-efficient heat transfer fluids. This leads us to the usage of other types of fluids that can be used to improve heat transfer. Based on these findings, the presence of nanoparticles increases the thermal conductivity without significant changes to the chemical and physical properties of the base fluid by dispersion of these nanoparticles in the base fluid and due to their higher stability, higher heat transfer capabilities and reduced particle clogging (Fsadni and Whitty, 2016 ; Singh and Gupta, 2016).The nanofluid flow around the micro-coil tube as compared with the constant flow of conventional fluid promotes a higher heat transfer coefficient. Thus, logic dictates that there can be higher thermal conduction and convection if a nanofluid alongside a configuration for the micro-coil tube would be significantly higher than the typical fluids alluded to earlier.

there are no studies of experimental and numerical related to pipe fitted with helical micro-coil tube. On the other hand, in the past, when a nanofluid was applied as working fluid, geometric structures and parameters of the microtube were not examined. Thus, to the best of the authors' knowledge, the effects of geometric structures and parameters on heat transfer characteristics and pressure drop in the helically coiled microtube heat exchanger with using nanofluids have not been reported. Therefore, this lack of knowledge motivated researchers to conduct this investigation. This gap can be fulfilled by incorporation of micro heat exchangers with nanofluids for further improved heat transfer rate concerning the individual use of a micro-coil or nanofluid flow.

1.4 Objectives of the Study

The major focus of this research is to study the heat transfer and fluid flow characteristics induced by compound technique using novel configurations of helical microtube inserts with metal and non-metal nanofluids to achieve the following specific objectives:

i. To numerically investigate effects of different parameters on the heat transfer and fluid flow characteristics.

ii. To determine the thermophysical properties of the prepared nanofluids.

iii. To design and fabricate experimental setup of fully developed flow regime to validate the numerical result of CFD simulation with experimental data of fully developed flow regime with optimum geometrical structures and parameters in (i).

iv. To develop new correlations for Reynolds Number with Nusselt Number and friction factor characteristics prediction for water and nanofluids with helical micro coil.

1.5 Scope of the Study

In order to achieve the mentioned objectives, the study will consists of the following:

i. The first part deals with the numerical simulation was carried out by using the commercial CFD package (ANSYS 18) to study the effect of helical micro coil configuration and nanofluid concentration on heat transfer augmentation and the friction factor for different values of Reynolds Number ranging from 200 to 1800 for hot fluid (nanofluids, water) through the micro coil and 5000 for cold fluid (water) through the shell. Three of helical microtube coil namely circle, oval and elliptical geometries with the same pitch-to-diameter ratio (p / d) is 1 and the same number of curvatures. The geometrical parameters of helical micro coil heat exchanger helical diameter and pitch values are 10, 14 and 18 mm respectively, and different nanoparticles (ZnO, SiO_2, Al_2O_3 and CuO) with water as base fluid of different volume fractions in the range at 1%, 1.5% and 2% .The diameter of nanoparticles (25, 50 and 75 nm) are used for investigation.

ii. The second part of work deals with the preparation and measurement of the thermophysical properties of nanofluids metal oxide (ZnO and Al_2O_3) with nanoparticle diameter 25 nm and volume fraction 1%, 1.5%, 2% because they were achieved the highest thermal performance factor than others of nanoparticles in the first objective.

iii. The third part of this work is to design and construct experimental setup of fully developed flow regime by using nanofluids (ZnO and Al_2O_3) with volume fraction 1%, 1.5% and 2%, nanoparticle diameter 25 nm at laminar flow with a range of Reynolds Number from 200 to 1800 through the helical microcoil as hot fluid and the Reynolds Number is 5000 through the shell as cold fluid, the inlet temperature of the hot fluid is 298 K and the temperature of the inlet cold fluid is 360 K, with circle helical micro coil in tube heat exchanger with 1.5 mm diameter at optimum helical diameter and Pitch in the first objective which is 18 mm and the number of curvatures are 28 mm in order to validate numerical results of CFD simulation.

iv. The fourth part of this work is to develop new correlations for Reynolds Number with Nusselt Number and friction factor characteristics prediction for Al_2O_3-water and ZnO-water nanofluids of 1.0%, 1.5% and 2.0% volume fraction by using least square regression analysis and SPSS Statistical Software package. Circle shape of helical microtube was considered as a coil of heat exchanger with ranges of pitch between 10 and 18 and constant pitch/diameter ratio under laminar flow at Reynolds number from 200 to 1800.

1.6 Significance of the Study

The heat exchange as a form of study has a wide array of applications which are both diverse and essential when it comes to developing and producing high efficiency heat exchangers. These devices are widely used in many industry, thus the research is justified via its importance through applicability. High performance heat exchangers allow for the saving of energy. However, there are limited researches when it comes to the performance increase of thermal systems on helical microtube heat exchanger by using CFD models. The benefits of heat transfer enhancement also have several positive for environmental issues and result in a considerable saving in the material cost.

Thus, the present work attempts to fulfil the existing gap in this particular area of research. The industrial applications of enhancing the heat transfer inside the helical microtube heat exchanger are to develop the microelectronic cooling techniques, the micro heat exchanger.

This new type of helical microtube can present a new breakthrough in the heat transfer performance against the common smooth micro tube. The outcome of the present study not only will advance the development of high efficiency heat exchangers and design more compact heat exchanger with a view to minimize the overall volume and cost of heat exchanger thus decrease the pumping power required for a given heat transfer process , but also can be used to other engineering applications such as :

i. Liquid rocket engine cooling.

ii. Hydrogen storage: storage volume is one of the major challenges to overcome before hydrogen become a viable fuel for automobile.

iii. MEMS: Micro-Electro-Mechanical Systems cooling.

iv. Transportation, biomedical, automobile industries, micro-reactors, and space applications such as gas turbines.

1.7 Thesis Organization

The thesis is divided in logical order into five chapters in order to facilitate the transition between chapters. Figure 1.1 shows the organization of this thesis.

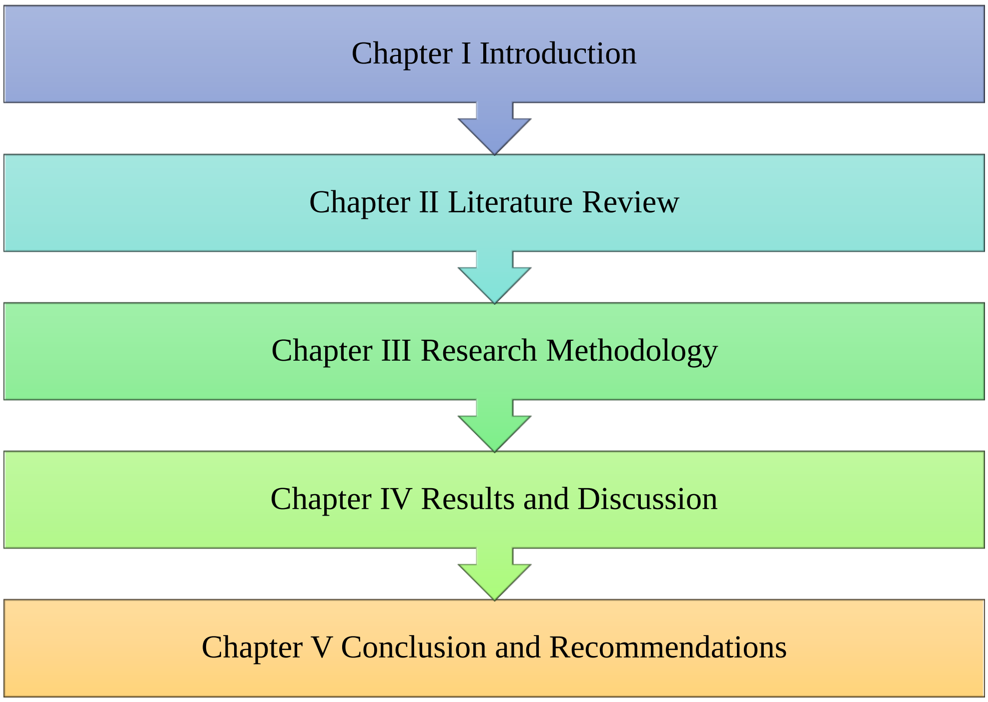

Figure 1.1 Thesis organization

Chapter I contains an introduction and research background including, general description of heat transfer enhancement. This chapter provides a general background that is used as an overview for the general reader. As such, the chapter has sections that include problem statement, research objectives and scope of research, the significance of study and finally, information about the thesis organization.

Chapter II contains an extensive review of heat transfer enhancement, especially using helical tube with nanofluid, microtubes and microchannels. All the relevant parameters effecting on heat transfer and friction factor characteristics are discussed. Previous researchers works are reported and their findings are summarized.

Chapter III describes the research methodology, including the experimental and Computational Fluid Dynamics (CFD) model simulation. Presents the design and fabrication of the experimental set-up. Techniques for pressure drop, fluid velocities and fluid temperature measurement have been displayed. Heat transfer and friction factor calculation based on these measurements. All the experimental measurements and test components and their functions are described in detail.

Chapter IV reports the results obtained from the experimental work and numerical simulation with a discussion of these results. In the numerical section, a computational fluid dynamics simulation is used to compute the 3-D steady viscous flows with heat transfer for plain tube fitted with a helical micro coil with different pitch and diameter, nanofluid in order to evaluate the effect helical microtube and nanofluid concentration on heat transfer enhancement. The simulation results were visualized using plots to understand the physical phenomena of heat transfer and friction factor. In the experimental section, the results obtained from measurements and calculations are described, in order to validate the observed results via the evaluation of the computational findings.

Chapter V presents the conclusion of the thesis with a summary and objectives that were achieved as well as the suggestions and recommendations for future work. Furthermore, the references of cited literatures, appendices and list of published papers are also presented.

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2. **Rasheed A. H.,** Alias HB, Salman SD. Thermophysical properties for ZnO-water nanofluid: Experimental study. SISTEC2020 conference: Materials Science Forum, Vol. 1025(2021), pp 9-14. **(Indexed by SCOPUS)**.