LAMINAR FLOW HEAT TRANSFER ENHANCEMENT IN MULTY-START SPIRALLY CORRUGATED TUBES

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ABSTRACT

Heat transfer plays an important role in many aspects of human life, especially the forced convection type. Hence, it has become very important to invest resources and efforts in this vital field to make some difference. Recently, the trend of using compact heat transport devices is of great interest to obtain an efficient, low cost and small size product which requires less production time with fewer efforts. Employing of artificial roughness, such as corrugation, for heat transfer enhancement in heat exchanger and other industrial thermal devices have shown promising results, with good performance reliability at lower cost. Therefore, the current study aimed to investigate experimentally and numerically the heat transfer enhancement and pressure drop increase in tubes with a superior type of corrugation i.e. the spiral corrugation. The flow of ionised water as working fluid in tubes at low Reynolds number was constructed to investigate the laminar flow regime of $100 \leq Re \leq 1300$. Five spirally corrugated tubes and one smooth tube under constant wall heat flux boundary condition with various thermo-physical properties was investigated through experimental test and computational fluid dynamics simulation. Different corrugation parameters, such as corrugation height to diameter and corrugation pitch to diameter ratios were studied in different corrugated tube sizes. The results showed that the severity index, which combines the effect of both corrugation height and pitch, has great effects on heat transfer rate, friction factor, and thermal performance of the flow inside spirally corrugated tubes. The heat transfer enhancement was in the range of 1.3-2 compared to a smooth tube, accompanied with an increase in friction factor in the range 1.1-1.9. The thermal performance range was found to be improved by 1.2-2.08 times. The heat transfer and friction factor correlation are proposed.

ABSTRAK

Pemindahan haba memainkan peranan penting dalam banyak aspek kehidupan manusia, terutamanya jenis pemindahan haba olakan paksa. Oleh itu, menjadi sangat penting untuk melabur dalam sumber dan tenaga usaha dalam bidang yang amat perlu ini untuk menghasilkan sesuatu perubahan yang ketara. Kebelakangan ini, penggunaan alat pengangkutan haba yang padat telah menjadi satu polar yang sangat menarik untuk meningkatkan kecekapan, menurunkan kos dan saiz produk sehingga boleh mengurangkan masa pengeluaran dan daya usaha. Penggunaan kekasaran tiruan, seperti permukaan kerut-beralun, untuk peningkatan pemindahan haba dalam penukar haba dan lain-lain peranti terma skala industri telah menampakkan kejayaan, dengan prestasi kebolehpercayaan yang baik dan kos yang lebih efektif. Oleh itu, kajian ini bertujuan untuk menyiasat melalui kaedah ujikaji dan berangka, peningkatan pemindahan haba dan pertambahan penurunan tekanan dalam tiub yang mempunyai kerut-beralun yang lebih unggul iaitu kerut-beralun pilin. Aliran air terion sebagai bendalir bekerja dalam tiub pada nombor Reynolds yang rendah telah dibina untuk menyiasat rejim aliran lamina yang mempunyai $100 \leq Re \leq 1300$. Lima tiub kerut-beralun pilin dan satu tiub licin di bawah keadaan sempadan fluks haba dinding pemalar dengan pelbagai sifat terma fizik disiasat melalui ujian ujikaji dan simulasi perkomputeran dinamik bendalir. Berbagai parameter kerut-beralun, seperti nisbah ketinggian kerut-beralun kepada garis pusat dan nisbah jarak alun kepada garis pusat dikaji dalam berbagai saiz tiub kerut-beralun. Hasil kajian menunjukkan bahawa indeks keamatan, yang menggabungkan kesan kedua-dua ketinggian kerut-beralun dan jarak alun, mempunyai kesan yang besar pada kadar pemindahan haba, faktor geseran, dan prestasi terma untuk aliran di dalam tiub kerut-beralun pilin. Peningkatan pemindahan haba adalah dalam julat 1.3-2 berbanding dengan tiub licin, dengan penambahan dalam faktor geseran dalam julat 1.1-1.9. Julat prestasi terma telah dapat diperbaiki sebanyak 1.2-1.9 kali ganda. Sekaitan pemindahan haba dan sekaitan faktor geseran telah dicadangkan.

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LIST OF ABBREVIATIONS

C/W	-	Twisted tape clearance ratios
CFD	-	Computational fluid dynamics
CITSG	-	Conical injector type swirl generator
CR	-	Conical-ring
DDIR	-	Discrete double incline ribs
DR	-	Divergent ring
DWs	-	Delta-winglet type vortex generator
e/D	-	Heat capacity of the fluid, kJ/kg·^{o}C
FEM	-	Finite element method
FVM	-	Finite volume method
Fw	-	Wave factor
MF	-	Mass flux
OHP	-	Oscillating heat pipe
p/D	-	Diameter of the tube, m
PCR	-	Perforated conical-ring
PR	-	Pitch ratio
TET	-	Twisted elliptical tube
TT	-	Twisted tape
WVG	-	Winglet type vortex generator
Y/W	-	Twisted tape twist ratios

LIST OF SYMBOLS

A - Surface area, m^2
C_p - Heat capacity of the fluid, kJ/kg·^{o}C
D - Diameter of the tube, m
e - Corrugation height
Gz - Graetz number
L - Length of the tube, m
k - Thermal conductivity, W/m·K
H - Heat transfer coefficient, W/m^2·K
N - Number of start riding
Nu - Nusselt number
P - Pressure, Pascal
p - Corrugation Pitch
Pr - Prandtl number
Pe - Peclet number
Re - Reynold number
T - Temperature, K
t - Time, s
u - Velocity, m/s
q - Heat flux at the wall, W/m^2

GREEK LETTER

μ	-	Dynamic viscosity of the fluid, kg·m/s^2
ρ	-	Density of the material, kg/m^3
η	-	Thermal efficiency
φ	-	Severity Index

SUBSCRIPT SCRIPT

B	-	Bulk
b	-	Bore
en	-	Envelope
n	-	Nominal
x	-	Local

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CHAPTER 1

INTRODUCTION

1.1. Problem Background

Heat transfer is the exchange of thermal energy between physical systems, depending on the temperature, by dissipating heat. The fundamental modes of heat transfer are conduction, convection and radiation.

Heat transfer always occurs from a region of high temperature to another region of lower temperature. Heat transfer changes the internal energy of both systems involved according to the First Law of Thermodynamics.

The flow of fluid may be forced by external processes, or sometimes (in gravitational fields) by buoyancy forces caused when thermal energy expands the fluid (for example in a fire plume), thus influencing its own transfer. The latter process is often called "natural convection". All convective processes also move heat partly by diffusion, as well. Another form of convection is forced convection. In this case the fluid is forced to flow by use of a pump, fan or other mechanical means.

Convective heat transfer, or convection, is the transfer of heat from one place to another by the movement of fluids, a process that is essentially the transfer of heat via mass transfer. Bulk motion of fluid enhances heat transfer in many physical situations, such as (for example) between a solid surface and the fluid. Convection is usually the dominant form of heat transfer in liquids and gases. Although sometimes discussed as a third method of heat transfer, convection is usually used to describe the combined effects of heat conduction within the fluid (diffusion) and heat transference by bulk fluid flow streaming.

The heat transfer is a very interesting field for economical, functional and environmental reasons; it is almost related to each aspect of human lives. Therefore, the enhancement of such field is quite essential, especially the forced convective heat transfer field. The conversion and utilization of energy in industrial, commercial, and domestic applications involve heat exchange processes. Some common examples are steam generation and condensation in power and cogeneration plants; sensible heating and cooling of viscous media in thermal processing of chemical, pharmaceutical, and agricultural products, refrigerant evaporation and condensation in air conditioning and refrigeration system, gas flow heating in manufacturing and waste-heat recovery; air and liquid cooling of engine and turbo-machinery systems, and cooling of electrical machines and electronic devices. Improved heat exchange, over and above that in the usual or standard practice, can significantly improve the thermal efficiency in such applications as well as the economics of their design and operation

The engineering cognizance of the need to increase the thermal performance of heat exchangers, thereby effecting energy, material and cost savings as well as mitigation of environmental degradation had led to the development and use of many heat transfer enhancement techniques. These methods have in the past been referred to variously as augmentation and intensification. One of the popular ways to enhance heat transfer which is recently of interests is using artificial surface roughness, ribs, grooves and corrugations. Spirally corrugated surface hold the promise of enhancing the heat transfer in tubes and, they are one of the most cost-effective enhancement methods.

Basically, there are two different methods to increase the rate of heat transferred and both of them are based on an enhanced heat transfer surface geometry to provide a higher thermal performance. One is the active method and the other is the passive method. The active technique requires external forces and the passive technique requires special surface geometries or fluid additives. The motivation behind this activity includes the desire to produce more effective heat exchangers and heat transfer enhancement in many other industrial applications. The ultimate objectives being to provide energy, material, and economic savings for the users of enhanced heat transfer technology.

Setting up a periodic disturbance along the streamwise is a favorable way to enhance the heat transfer in forced convection due to its simplicity and effectiveness as Adachi and Uehara reported [1]. This kind of periodical retardation plays a vital rule in the enhancement process by breaking the thermal boundary layer and distorts the temperature field of the fluid flowing inside the tube; hence it will minimize the resistance or the reluctance to the heat transfer. This mechanism is widely mentioned and cited by researches as it clearly described and reviewed in Chapter 2.

Corrugation helps on increases heat transfer enhancement due to the presence of secondary movements of the fluid adjacent to the wall. Unfortunately, in spite of the importance of the corrugation in various industrial applications, there is not enough publications concerning the corrugation employment in heat transfer enhancement. Only recently, the employing of corrugation for the enhancement of heat transfer has become interesting because it has the combined merits of extended surfaces, turbulators and roughness as shown in Figure 1.1.

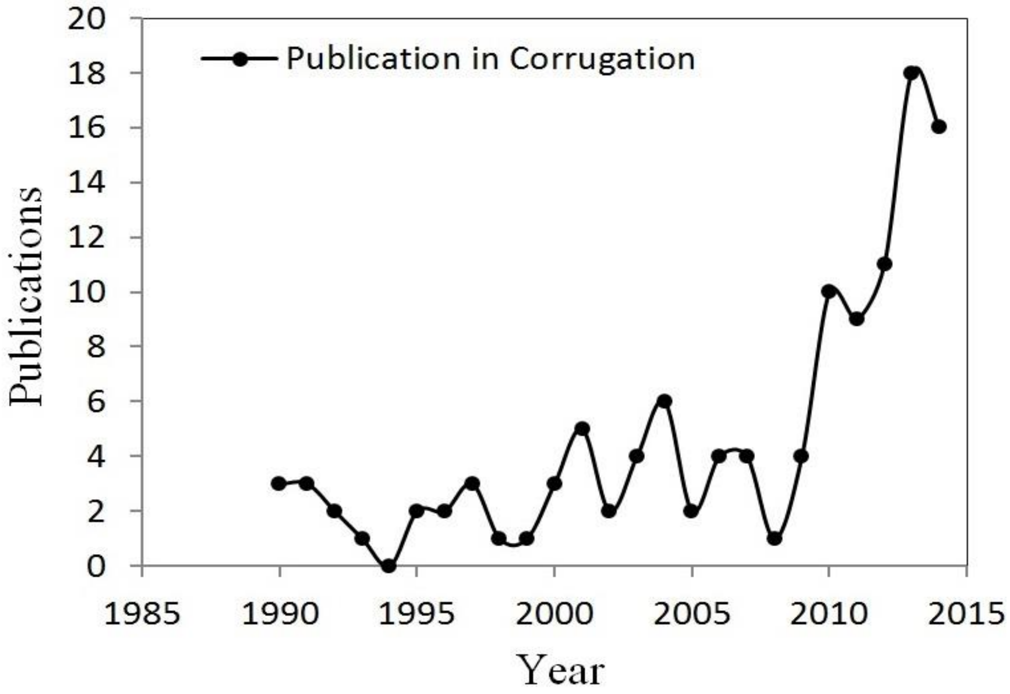

Figure 1.1 Publications regarding the corrugation in heat transfer enhancement [1]

Therefore, the emphasis was given in this investigation research to the use of the spiral corrugation in heat transfer enhancement.

In the last few years, the attention was given to the importance of using corrugation in the heat transfer enhancement due to the mentioned merits. In addition, the main functions of corrugation are to promote the secondary recirculation flow by inducing radial velocity components, mixing the flow layers and finally, increasing the wet perimeter with holding the throat cross-section area constant.

There is enough number of investigators whom tried to study the heat transfer enhancement in both ways, experimentally and numerically. A different corrugation profiles and arrangement were employed. Many fluids were tested inside various tube arrangements. But yet, the studies concerning the employing of both experimental and numerical techniques for the determination of thermal performance of spirally corrugated tubes for the flow of water at low Reynolds number are limited in spite of the thrust for a smaller size, cost effective thermal transport devices [2]. In addition, the traditional corrugation profile was also used over and over, and the creativity regarding the corrugation profile and its effect was completely neglected.

1.2. **Problem Statement**

As it is commonly known, energy resources is exhausting at a tremendous rate; hence, it has become important to improve the heat transfer characteristics of tubes in view of the energy situation and to avoid the issues of imminent energy lack with suitable and well functional precautions. The passive heat transfer enhancement basically based on the adopting of many tools that induces a swirl and vorticities at the secondary flow region, which mixed the fluid layers and increasing the surface area. However, the passive technique involving so many ways like twisted tapes, fins, ribs, rough surface, additives, extended surfaces, wire coil insert and corrugations. Corrugated tubes are a type of enhanced heat transfer tool which has become very interesting in the past few years.

Adopting a disturbance source in the flow direction is a preferred method for the heat transfer enhancement. Setting up a disturbance promoter, which periodically gags the flow along the streamwise to improve the heat exchange performance is a common technique for the interrupting of the thermal boundary layer and mixing the flow.

The main functions of corrugation are to promote the secondary recirculation flow by inducing radial velocity components, mixing the flow layers and finally, increasing the wet perimeter with holding the throat cross– section area constant, which leads to increases the convective surface area. Therefore, it was extensively used in modern heat exchangers and other heat transport devices. Especially in the food industry, where the flow is should be at low Reynolds number. Hence, this kind of tube would be helpful in the heat treatment process of juices flowing in tubes. It will give good results with minimum requirements. Spiral corrugation increases heat transfer enhancement due to the presence of secondary movements of the fluid adjacent to the wall. Therefore, the emphasis was given to the use of corrugation in heat transfer enhancement.

1.3. Research Hypothesis

The primary flow of fluid in tube with spiral corrugated surface extension induced a secondary flow inside the corrugation. This secondary flow is most probably of the vortex swirl flow type. The interaction of primary pipe flow and the swirl secondary flow will produce a unique flow pattern. This unique flow pattern which can be studied using high fidelity computational fluid dynamics (CFD) techniques could be deduced in term of the heat transfer performance.

1.4. Research Questions

a) How corrugation height to diameter (e/d) affect heat transfer enhancement?
b) What are the effects of corrugation pitch to diameter (p/d) on heat transfer enhancement?
c) Does the number of corrugation (N) affect the heat transfer enhancement?

d) What is the mechanism that are heat transfers enhancement in spirally corrugated tubes?
e) Can this mechanism be studied effectively using CFD simulation?

1.5. Objectives

The main objective of this study to determine the optimum corrugation of spirally corrugated tube with highest heat transfer enhancement and with a minimum pressure drop penalty. In order to achieve this aim, the following sub objectives are intended to be achieved:

a) To enhance the heat transfer by utilizing some modified spirally corrugated tubes. This objective would be achieved by testing different corrugation height to diameter *e/d* and corrugation pitch to diameter *p/d* to produce swirl secondary flow and boundary layer, which means more heat transfer
b) To simulate a double, triple and multiple corrugations starts of circular profile by using commercial CFD software for the tube to increase heat transfer and decrease pressure drop, while a single smooth tube of certain specifications will be employed in experiments for validation purposes.
c) To determine the thermal performance factor (η) for each tube. In addition, to determine the number of start N effects on both heat transfer and pressure drop.

1.6. Scope of Research

This study shall focus on the followings:

a) Laminar forced convective heat transfer of a Newtonian fluid flow in spirally corrugated tubes will be considered.

b) Water will be taken as a working fluid and the flow will be assumed as steady and incompressible. The fluid properties such as viscosity μ, heat capacity c_p and thermal conductivity k will be taken as a function of temperature.

c) The investigation will be carried out numerically and experimentally under a constant wall heat flux condition for $100<Re<1300$ and for various geometrical parameters in order to get wide range of database.

1.7. Significance and Contributions of this Study

The current study focused on laminar flow of water in corrugated tubes to enhance the heat transfer rate because there is a lack in the experimental studies concerning this subject in the literature as depicted in the next chapter in Section 2.4.

In addition, there are only three authors whom proposed correlations of Nusselt number and friction factor for the laminar flow of water in annuli or fluted tubes without taking the effect of severity index in to the account, and there is no correlations regarding the corrugated tube.

1.8. **Organization of the Thesis**

This thesis consist of six chapters, each one deals with specific aspect. Chapters (1-2) provide a general introduction and thesis headlines, in addition to the deep and comprehensive review of the problem. While Chapters (3-5) provide the detailed methodology and tools to investigate and solve the problem. Chapter 6 presents the outcomes and its interpretations.

Chapter 1 presents the general information about the problem and it is nature, as well problem background. In addition, the motivation behind the need of the current investigation and close scope on the problem with its limitations.

Chapter 2 involved the literature review and the research that conducted in the past which are related to the current investigation research. It shows a comprehensive and criticized review of about 95% of studies concerned with heat transferred by corrugation. In addition it contains the summary of all the related studies.

Chapter 3 depicts and describes the experimental methodology of the research. Hence, it consists of the experimental rig description, experimental procedure, experimental measurements and instrument calibration.

Chapter 4 explains the mathematical modelling and simulation steps. It’s also explained in details the modeling of the problem besides the validation and verification of the simulation process. The number and characteristics of the numerically tested tubes were also depicted in this chapter. In addition to the mesh process and convergence criteria.

Chapter 5 shows the results and their discussions. It also shows the effect of different parameters that have significant effects on the results with reasonable explanations. This chapter also presents the extracted correlations for the heat transfer and friction factor.

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