Ministry of Higher Education
and Scientific Research
University of Diyala
College of Engineering

EXPERIMENTAL AND NUMERICAL EVALUATION OF DOUBLE COIL PIPES HEAT EXCHANGER

A Thesis Submitted to the Council of College of Engineering,
University of Diyala in Partial Fulfillment of the Requirements for
the Degree of Master of Science in Mechanical Engineering

By

Ali Najm Abed

(B. Sc. Mechanical Engineering, 2017)

Supervised by

Prof. Dr. Abdul Monem Abbas Karim

Asst. Prof. Dr. Itimad Dawood Jumaah Azzawi

2022 A.D 1443 H

بِسۡمِ ٱللَّهِ ٱلرَّحۡمَٰنِ ٱلرَّحِيمِ

{نَرْفَعُ دَرَجَاتٍ مَنْ نَشَاءُ وَفَوْقَ

كُلِّ ذِي عِلْمٍ عَلِيمٌ}

صدق الله العلي العظيم

(يوسف ٧٦)

ACKNOWLEDGEMENTS

All praises to Allah for the strengths and His blessing in completing this thesis.

I would like to express my appreciation and gratitude to my supervisors, ***Prof. Dr. Abdul Munem A. Karim*** *and* ***Asst. Prof. Dr. Itimad D. J. Azzawi*** *for their supervision and constant support, their invaluable help of constructive comments and suggestions throughout.*

I express my special thanks and my sincere prayers to the soul of the greatest Arab poet, ***Muhammad Mahdi Al-Jawahiri****, for the support I received from his poetry and his unique personality.*

Also, I am extremely grateful to my parents, brothers and sisters for their love and sacrifices for educating and preparing me for my future.

Finally, my thanks go to all the people who have supported me to complete the research work directly or indirectly.

Abstract

In the current work, substantial research and cost-effective strategy have been conducted to enhance the thermal efficiency of shell and coil heat exchangers, and geometrical modification is one technique to improve the exchange of thermal energy between two or more fluids. Several studies have emerged about enhancing heat transfer with helical coils widely used in industrial applications such as chemical processes, power generation, electronics, etc. Initially, a practical experiment to check results of the numerical analysis on a double coil heat exchanger has been conducted. The results of the numerical study showed high agreement with the experimental results.

The numerical analysis was conducted to find the impact of using double coil heat exchanger with multiple pitches on the ability of the exchanger to improve the heat transfer process. The main objective of this simulation is to determine the appropriate configuration of the shell and helical tube heat exchanger to obtain high thermal performance. Following the encouraging simulation results, a double coiled tube with multiple pitches was manufactured, as well as a single coiled tube, to compare the results and confirm the effectiveness of the correlation between the changes in the pitch, while maintaining the basic design parameters in terms of tube diameter (d_c), shell diameter (D_{sh}) height of shell (H_{sh}) and, the height of coil (H_c).

The numerical study showed high agreement with the experimental data, with the error rate being about 9%. The results showed that at the same length of the tube, the use of the double tube led to an improvement in the heat transfer process, as the improvement rate in the average heat transfer coefficient was 10% compared to the single coil. In general, the new double-tube design (P-2P-P) has led to an improvement in the heat transfer process (5%), which is evident from the increase in the efficiency of the exchanger, the overall heat transfer coefficient, and the preparation of the Nusselt number for the shell side when preparing Reynolds ($400 < Re_{sh} < 2000$) by 26%, 22%, 19%, respectively.

Contents

Title	Page No
Abstract	i
Contents	ii
List of tables	iv
List of figures	v
Nomenclature	vii
Chapter One: Introduction	
1.1 Introduction	1
1.2 Helically coiled Pipe and shell	3
1.3 Aim and Objectives	6
1.4 Outline of the Thesis	7
Chapter Two: Literature review	
2.1 Introduction	9
2.2 The Numerical Studies	10
2.3 The Experimental Studies	16
2.4 The Experimental and Numerical Section	20
2.5 Summary	23
Chapter Three: Numerical Methodology	
3.1 Introduction	24
3.2 Geometry Generation	26
3.3 Mesh Generation and Mesh Independency Study	29
3.4 Flow Specifications and Governing Equations	31
3.5 Boundary Conditions	34
3.6 Assumptions	36
3.7 Calculation and Numerical Solution	36
Chapter Four: EXPERIMENTAL WORK	
4.1 Introduction	38
4.2 Experimental Apparatus	38

4.3 Water Circulation System 42
4.4 The Measuring Devices 42
4.5 Experimental Procedure 45

Chapter Five: Results and Discussion

5.1 Introduction 48
5.2 Numerical Study Results 48
5.3 Experimental Study Results 56

Chapter Six: Conclusions and Recommendations

6.1 Conclusions 66
6.2 Recommendations 67
References 68
Published Research
Appendix A: Uncertainty Analysis

LIST OF TABLES

Table No.	Table Title	Page No.
1-1	Classification of techniques for enhancing heat transfer	2
3-1	Geometric parameters of a variable pitch double coil heat exchanger	27
3-2	Mesh independency study	30
3-3	Mass flow rate at the inlet	35
3-4	Higher values of the variables	37
4-1	Details of shell and helically coiled tube heat exchanger	41
4-2	Test conditions for the current experiments	46
4-3	Average uncertainties of the performance parameters	47
5-1	Results of previous papers with current study	64

LIST OF FIGURES

Figure No.	Figure Title	Page No.
1.1	the main parameters of a typical helical coiled tube	4
1.2	Secondary flow for low and high Dean Numbers	5
2.1	Schematic of the 3D fluid domain with insert twisted coil tape	11
2.2	Flow development through the straight tubes: a) angle 9, b) angle 15, c) angle 30 and d) angle 45	12
2.3	polyhedral mesh for different modified shaped tubes	15
2.4	a) Tube in tube helical coil heat exchanger, and b) Grid topology	16
2.5	shell and helically coiled tube heat exchanger a) Theoretically, b) Experimentally	22
3.1	ANSYS fluent modeling diagram	25
3.2	Schematic of the shell and double coil tube (baseline case)	27
3.3	Various simulated models of double heat exchanger a) P-2P-P at P=20mm, b) 2P-P-2P at P= 20mm, c) P-2P-P at P= 30mm, d) 2P-P-2P at P= 30mm, e) P-2P-P at P= 40 mm, f) 2P-P-2P at P= 40mm	28
3.4	Generated mesh for Shell side and double coil pipe	29
3.5	Temperatures of the heat exchanger's output with various numbers of cells	30
4.1	a) Image setup experimental work of double coil, b) Schematic diagram of the experimental set up	39
4.2	Schematic diagram of the test section (baseline case)	41
4.3	flow meter a) hot water, b) cold water	43
4.4	thermocouple (K- Type)	44
4.5	Data logger HT-9815	45
5.1	Validation study for a single coil inside the shell	49
5.2	Validation study for a double coil inside the shell	49
5.3	Heat flux of single and double coil with different mass flow rates	50
5.4	Variation of the heat flux with coil side Reynolds number 11100 2P-P-2P at P=40mm, P-2P-P at P= 40mm, 2P-P-2P at P= 30mm, P-2P-P at P= 30mm, 2P-	52

	P-2P at P= 20 mm, P-2P-P at P= 20mm, and conventional pitch	
5.5	Heat flux variation at different mass flow rate	53
5.6	Temperature distribution in two models, a) conventional pitch heat exchanger, b) double coiled with modified pitch P-2P-P	54
5.7	Temperature distribution in shell side from side view; a) Conventional pitch, b) Modified pitch	55
5.8	Velocity distribution at the shell side of a double coil modified pitch at a) m_{sh}= 2 Lpm. b) m_{sh} = 8 Lpm	56
5.9	a comparison of the numerical simulation and experimental findings for the Nusselt number on the shell side vs. the Reynolds number	57
5.10	Overall heat transfer of two double-helical coil models	58
5.11	Heat transfer coefficient of two double-helical coil models	59
5.12	Effectiveness of two double-helical coil models	60
5.13	NTU of two double-helical coil models	60
5.14	Nusselt numbers of two double-helical coil models	61
5.15	The Nusselt number for the shell side compared between the four models	62
5.16	Numerical Nusselt numbers on the shell side compared to anticipated Nusselt numbers throughout a range of Reynolds values on the shell side	63

NOMENCLATURE

Symbol	Units	Definition
A	m^2	Area
C_p	J/(kg.K)	Specific heat
d	m	Pipe diameter
D_c	m	Curvature diameter
De		Dean number
D_h	m	Heat exchanger hydraulic diameter
f		Friction factor
H	m	Heat exchanger height
h	W/m^2K	Heat transfer coefficient
k	W/(m ◦C)	Thermal conductivity
L	m	Length of coils
$\dot{m}$	Lpm	Mass flow rate
N		Number of coil turns
Nu		Nusselt number
NTU		Number of heat transfer unit
P	m	Coil pitch
Pr		Prandtl number
Q	W	Heat transfer rate
q	W/m^2	Heat flux
Re		Reynolds number
T	℃	Water temperature
t	m	thickness
U	W/m^2K	Overall heat transfer coefficient
V	m/s	Velocity
Greek letters		
γ		Dimensionless pitch ratio
ρ	kg/m^3	Density

μ	kg/(m.s)	Dynamic viscosity
ε		Effectiveness
$\Delta TLMD$	K	logarithmic mean temperature difference
Subscripts		
Avg		Average
c		Coil side
co		Cold
h		Hot
i		Inlet
o		Outlet
sh		Shell side
w		Wall

Chapter One

Introduction

1.1 Background

Heat transfer between flowing fluids is one of the most essential physical phenomena that has attracted researchers' interest for a long time. Different types of heat exchangers are utilized in various combinations to achieve higher heat transfer rate. Regardless of how these exchangers are designed, they are all linked by a basic idea that allows thermal energy to be transferred between two different fluids at different temperatures. The heat exchanger is used in a variety of applications, including energy generation, the chemical and food industries, electronics, and environmental engineering [1and 2]. Moreover, heat exchangers are among the most often used equipment in the manufacturing industry, since they are utilized in a variety of activities such as cooling, heating, condensation, boiling, and evaporation. Heat exchangers are grouped into several types and designs based on their function and shape. For example, heat exchangers used for condensing are referred to as condensers, while heat exchangers used for boiling are referred to as boilers.

The performance of any type of heat exchanger is measured by the amount of heat transferred (heat transfer enhancement) and pressure drop, and this pressure drop provides insight into the capital cost and energy requirements (operating cost) of the heat exchanger. Enhancement strategies generally lower the thermal resistance of a traditional heat exchanger by generating a greater convective heat transfer coefficient, with or without increased surface area (as represented by extended surfaces or fins). As a consequence, a heat exchanger's size can be lowered, its heat duty can be increased, the pumping power needs can be reduced, and the exchanger's working approach temperature difference can be minimized [3]. Therefore, heat transfer enhancement processes fall into two categories: active and passive methods, which are detailed in Table 1-1, however it is indicated that two or more of these techniques can be used at the same time to provide a better result than a single strategy alone[3]. As a link between passive and active techniques, the third method for enhancing heat transfer is described as “combined techniques”, using the rough surface with fluid vibration and the rough surface with a twisted bar as examples [4]. In general, the efficiency of any of these approaches is highly dependent on the heat transfer mechanism as well as the kind and application of the heat exchanger. The descriptive characterization of each of the approaches is useful in assessing their potential when considering their unique applications.

Table 1-1: Classification of techniques for enhancing heat transfer [3].

Active Techniques	Passive Techniques
Fluid vibration	Additives for liquids
Mechanical aids	Additives for gases
Surface vibration	Swirl flow devices
Injection	Extended surface
Suction	Roughness surface
Electrostatic fields	Treated surface
Jet	Surface tension devices
	Displaced enhancement devices
	Coiled tubes

1.2 Helically Coiled Pipe and Shell

Many researchers have been interested in the flow in curved tubes since they were first discovered because of their importance in a variety of technical applications such as nuclear reactors and heat exchangers. The nature of flow through a coiled tube differs significantly from that of a straight tube, resulting in the development of centrifugal forces in the flow via coiled tubes, which create secondary flow. Turbulence is caused by these secondary flows, which improves the heat transfer rate in coiled tubes [5]. Due to the vortex flow inside the coil tube, secondary flows are formed, which tends to increase the length of effective fluid flow through the tube, resulting in increased heat transfer. The impact of curvature on fluid viscosity in a coiled tube was originally recognized by Grindley and Gibson [6]. Moreover, the centrifugal forces generated by the tube's bending create a secondary flow field (superimposed on the main axial flow) with a rotating motion that pulls the fluid particles towards the tube's core. The strength of the secondary flow field grows as the flow rate increases, and because of the stabilizing effects of this secondary flow, the laminar flow of Reynolds numbers in helical coils remains significantly higher than in straight tubes. As a result, in laminar flow, the variations in heat transfer performance between straight coils and tubes are particularly noticeable [7]. Figure (1.1) shows the main parameters of a typical spiral coiled tube. These geometric parameters include tube diameter (d), coil diameter (D), and coil pitch (p).

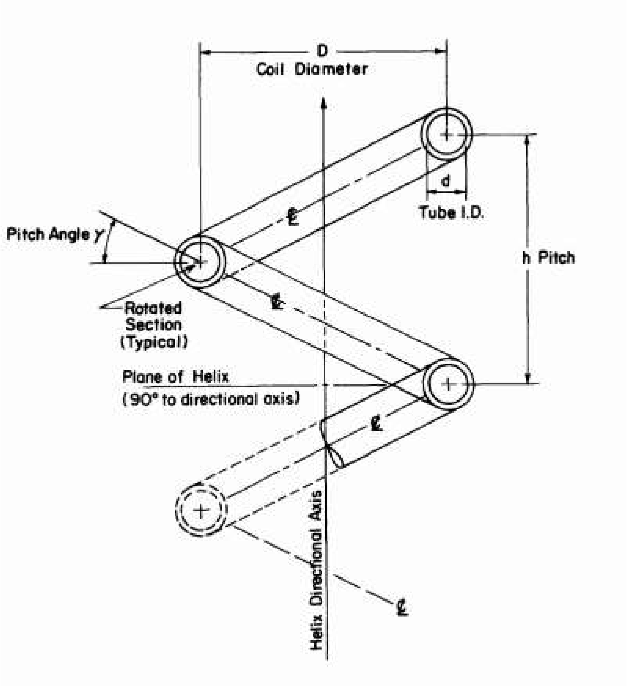

Figure (1.1) the main parameters of a typical helical coiled tube [7].

The flows that follow a curved path create a centrifugal force that pushes the faster liquid particles outwards and at the same time the slower particles are pushed inwards, the slower particles suffer from less centrifugation effect while the faster particles suffer from higher centrifugal forces due to the accepted fact that the centrifugal force depends on Domestic axial speed [8]. The fluid velocity is highest at the centre of the tube if the fluid flows through a straight tube and is zero at the tube wall and is symmetrically distributed around the axis. In the case of a bent tube, the primary velocity profile is deformed by adding the secondary flow pattern. The secondary flow is created by centrifugal forces. The position of the maximum axial velocity moves toward the outer wall of the curved tube, as mentioned by Williams and Dean for the first time. These researchers showed that the slightly curved tubes mainly depend on a one-dimensional parameter called Dean Number:

$$De = Re\ (\frac{d_c}{D_c})^{0.5} \tag{1-1}$$

Centrifugal forces lead to a secondary flux consisting of a pair of anti-rotating cells called dean cells as shown in Figure (1.2) below. For higher Dean Numbers, centrifugal instability appears near the outer wall, which in turn generates an additional pair of counter vortices for rotation known as “Dean Vortices”. Due to the imbalance between the centrifugal forces and the viscous forces, the cells of the dean are present in even the smallest number of deanships. This movement is due to the centrifugal forces caused by bending the tubes and leads to energy loss. This movement is not parallel in the stream flow through straight tubes [4].

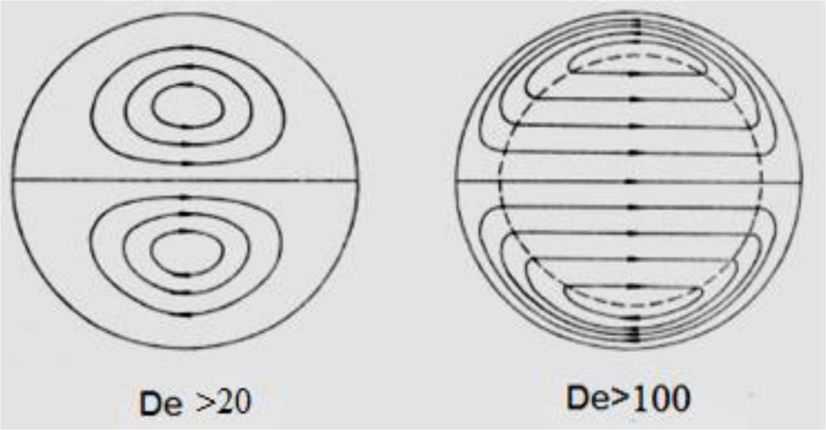

Figure (1.2) Secondary flow for low and high Dean Numbers [4]

Most of the researchers worked on further improving the thermal performance of coiled helical tube heat exchangers that depend on numerical analysis using various computing programs such as (Computational Fluid Dynamics (CFD)). CFD is the use of computer simulations to analyze systems including fluid flow, heat transfer, and related phenomena such as chemical reactions. This approach is quite durable, and it may be used in a variety of industrial and non-industrial applications such as aircraft and vehicle aerodynamics, power plants, biomedical engineering, and so on. [9].The ability to model 3D geometries, which allows for the measurement of improvements, is a key element of the CFD technique. In earlier studies, a wide variety of numerical literature has tried to enhance the heat transfer rate by employing a single and double helical coil heat exchanger with much less time and expense than what is necessary for laboratory research [10]. However, this does not invalidate the relevance of laboratory research, which provides a strong foundation for each study and strengthens theoretical conclusions.

1.3 Aim and Objectives

The design of shell and helical coil heat exchangers is a very important subject in industrial processes due to their design, high-cost production and highly efficient. Based on the literature reviewed, many researchers studied enhancing heat transfer by using the single helical coils that are widely used in industrial applications, such as food and chemical processes, power generation, electronics and nuclear industries, etc. Therefore, to enhance the heat transfer rate in shell and coil heat exchanger, an experimental and numerical investigation will be conducted in the present using double coil heat exchanger to reach the main aim and hence the following objectives should be considered:

- ✓ The geometrical characteristics of the coil side, such as single coil, double coil, and pitch coil, should be considered in order to improve the heat transfer rate.
- ✓ The first section seeks to provide a validation study between the current study and previously published work in terms of the Nusselt number shell side, NTU and Reynolds number utilizing single and double coils heat exchanger (baseline case) using pure water.

- ✓ Once the numerical findings are consistent, additional numerical analyses are conducted over a double coil heat exchanger at constant temperatures using various coil pitches and mass flow rates.
- ✓ After the optimum configuration in terms of heat transfer rate has been numerically established, this model will be manufactured to verify that the experimental and computational findings are consistent.
- ✓ Finally, a correlation between the predicted and numerical Nusselt number of the shell side would be established over a wide range of Reynolds numbers.

Outline of the Thesis

This thesis is divided into six chapters as follows:

- ➢ Chapter one provides a general introduction to the improvement in the heat transfer process, as well as an introduction to helical coiled tubing and the effect of bending on secondary flow construction.
- ➢ Chapter two presents a literature review of recently published papers and research progress in investigating the optimization of the heat transfer process in helical-coiled tubes. This chapter is divided into three main sections: the first section is the numerical studies, the second is the experimental studies, and the third is the numerical and experimental studies. Each section describes different parameters that affect the rate of heat transfer.
- ➢ Chapter Three describes the procedure of the geometry construction and then explains how the mesh is selected and generated. In this chapter, mesh analysis has been introduced to optimize the mesh through testing five different mesh configurations and selecting the most appropriate mesh which

can capture the required data. Furthermore, The equations used and the boundary conditions are explained.

- Chapter four explains the implementation of the practical aspect in the current study by showing the method of connecting devices and the different shapes of the spiral coil. The chapter also provides an explanation of the devices used during the experiments and their accuracy.
- Chapter five presents, with the help of graphs and figures, the results of the validation of previous research and the results of the current study. This chapter is divided into two parts: the numerical results section, and the experimental results section.
- Chapter six, concludes by summarizing the main findings, and proposals for possible future work are also examined.