R.T.
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCE

EXPERIMENTAL ANALYSIS OF THE SINGLE PHASE PRESSURE DROP CHARACTERISTICS OF SMOOTH AND MICROFIN TUBES

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A MASTER OF SCIENCE THESIS
DEPARTMENT OF MECHANICAL ENGINEERING
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This paper, which is prepared by ALİ CELEN has been accepted as a **MASTER of SCIENCE THESIS** in the department of Mechanical Engineering of The Graduate School of Natural and Applied Sciences by the juries given below on 24.01.2013.

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This thesis investigates the single phase pressure drop characteristics of smooth and microfin tubes experimentally.

January, 2013

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LIST OF SYMBOLS

A	Actual flow area of tube [m^2]
A_n	Nominal flow area of tube [m^2]
D_i	Inside tube diameter [m]
d_h	Hydraulic diameter [m]
D_e	Equivalent tube diameter [m]
D_o	Outside tube diameter [m]
e	Height of fin [m]
f	Friction factor
G	Mass flux [kg $m^{-2}s^{-1}$]
L	Length of test tube [m]
l_c	Characteristic length [m]
m	Mass flow rate [kg s^{-1}]
n	Number of fins
N	Number of experiments
p	Fin pitch (m)
s	Average fin thickness [m]
ΔP	Pressure drop [mbar
Re	Reynolds number
t	Fin tip thickness (m)
V_m	Average fluid velocity [ms^{-1}]
E	Fin or roughness height [m]
μ	Dynamic viscosity [Pa.s]
α	Helix angle (^{o})
ρ	Density [kg m^{-3}]
τ	Shear stress [N m^{-2}]

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ABSTRACT

EXPERIMENTAL ANALYSIS OF THE SINGLE-PHASE PRESSURE DROP CHARACTERISTICS OF SMOOTH AND MICROFIN TUBES

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Department of Mechanical Engineering
MSc. Thesis

Advisor: Assist. Prof. Dr. Ahmet Selim Dalkılıç

In this study, the single phase pressure drop characteristic of smooth and microfin tube are investigated experimentally. The horizontal test section is counter flow double tube heat exchanger with water flowing in the inner tube and cooling water flowing in the annulus. By means of experimental setup, required temperature and pressure measurements are recorded and friction factor coefficient and pressure drop of smooth and microfin tubes are determined. Experiments are conducted for mass flow rates in the range between 0.023kg/s and 0.100 kg/s and effect of Reynolds number on pressure drop is investigated. By using experimental results, Blasius type friction factor equations are developed for both smooth and microfin tubes. Experimental results for both smooth and microfin tubes are compared with correlations given in the literature.

Key Words: Microfin tube, Pressure drop, Friction factor, Single-phase flow

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ÖZET

TEK FAZLI AKIŞTA PÜRÜZSÜZ VE MİKROKANATLI BORULARDA BASINÇ DÜŞÜMÜ KARAKTERİSTİKLERİNİN DENEYSEL OLARAK İNCELENMESİ

Ali CELEN

Makine Mühendisliği Anabilim Dalı
Yüksek Lisans Tezi

Tez Danışmanı: Yrd. Doç. Dr. Ahmet Selim Dalkiliç

Bu çalışmada tek fazlı akışta pürüzsüz ve mikrokanatlı borularda basınç düşümü karakteristikleri deneysel olarak incelenmiştir. Test bölgesi, iç boruda ve halka kısmında su kullanılan karşı akışlı çift borulu ısı değiştiricisidir. Gerekli sıcaklık ve basınç ölçümleri kaydedilmiş ve pürüzsüz ve mikrokanatlı boruya ait sürtünme katsayısı ve basınç düşümü belirlenmiştir. Deneylerde kütlesel debi 0.023 kg/s ve 0.100 kg/s aralığında değiştirilmiştir ve Reynolds sayısının basınç düşümü üzerine etkisi incelenmiştir.Deneysel sonuçlar kullanılarak pürüzsüz ve mikrokanatlı borular için Blasius tipi sürtünme katsayısı denklemleri geliştirilmiştir. Deneysel sonuçlar pürüzsüz ve mikrokanatlı borular için literatürde bulunan denklemlerle karşılaştırılmıştır.

AnahtarKelimeler: Mikrokanatlı boru, Basınç Düşümü, Sürtünme Katsayısı, Tek Fazlı Akış

YILDIZ TEKNİK ÜNİVERSİTESİ FEN BİLİMLERİ ENSTİTÜSÜ

CHAPTER 1

INTRODUCTION

In engineering applications it is important to transfer heat to from one fluid to another efficiently. The equipments which are used in order to transfer heat are called heat exchangers. Heat exchangers are used in a wide variety of applications. These include power production, chemical and food production industries, electronic, environmental engineering, waste heat recovery, manufacturing industry, air conditioning, refrigeration and space applications.

In today's world, heat transfer enhancement has become very important issue. Heat transfer enhancement in heat exchangers result in reduced size, low cost and improved heat transfer performance. There are two techniques for heat transfer enhancement: Active and passive techniques. First one is not popular technique because it requires the addition of external power.

Passive heat transfer enhancement consists of alteration to the heat transfer surface such as extended surfaces, treated surface etc. Among the passive heat transfer enhancement techniques, the usage of microfin tubes are very popular because of their high heat enhancement and low increase in pressure drop when they compared with smooth tube. Fuji et al. [1] invented the microfin tube. Geometric parameters which characterize microfin tubes are outside diameter, inside diameter, number of fins (ranges between 50-70), helix angle (ranges between 10^o-35^o) and fin height (ranges between 0,1-0,4 mm). If the ratio of height and inside diameter of a microfin tube is between 0,02 and 0,04, this tube is classified as microfinned tube.). If the ratio of height and inside diameter of a microfin tube is higher than 0,04, this tube is classified as finned tube. Microfin tubes are commonly used in HVAC applications (condensers and evaporators for cooling systems).

1.1 Literature Review

Wang et al. [2] performed an experimental study related to single phase heat transfer and pressure drop characteristics of micro-fin tubes. In their study, they used double-pipe heat exchanger with water as test fluid and tested a smooth tube and seven micro-fin tubes each having different geometrical parameters. Wilson plot technique is used in order to determine inside and outside heat transfer coefficients of test tubes. Their study showed that critical Reynolds number is important parameter for enhanced heat transfer. They suggested that heat transfer data can be correlated by using heat-momentum transfer analogy instead of Dittus-Boelter type equation. As a result of their study, they produced heat transfer correlation in the range of $2500<Re<4000$ which can predict micro-fin data with high accuracy.

Copetti et al. [3] compared experimentally heat transfer performance of smooth and micro-fin tubes at different flow rates. In the experimental set up, water is used as test fluid and tubes having 9.52 mm diameter is used. They compared measured friction factor data with Petukhov and Blasius equations and heat transfer coefficient data with Dittus – Boelter and Gnielinski equations. They developed correlations for prediction of micro-fin heat transfer data and compared them with experimental results. The experimental study showed that heat transfer coefficient of micro-fin tube was 2.9 times higher than smooth tube in turbulent flow. Although pressure drop of micro-fin tube was 1.7 times higher than smooth tube, heat transfer increase was approximately 80%.

Wei et al. [4] presented experimental study in order to determine single phase heat transfer and pressure drop in micro-fin tubes by using water and oil as working fluids. In the study, experiments were conducted for Reynolds number ranging between 2500 and 90000 and Prandtl number varying between 3,2 and 220.Their study showed that critical Reynolds number is important parameter for heat transfer enhancement. In case of Reynolds number is below critical Reynolds number micro-fin tubes behave as smooth tube. For Reynolds numbers higher than critical Reynolds number, heat transfer enhancement can be observed. Their studies showed that heat transfer performance of micro-fin tube for Reynolds number greater than 30000 with water as working fluid is two times higher than smooth tube. Friction factors of smooth and micro-fin tubes are just about equal for Reynolds number less than 10000 but friction factor of micro-fin tube is 40-50% higher when it is compared with smooth tube for Reynolds number higher than 30000.

Siddique and Alhazmy [5] studied heat transfer and pressure drop characteristics inside micro-fin tube for single phase flow. Double pipe heat exchanger and micro-fin tubes having 7.94 mm outside diameter were used in the experimental set up. They correlated a Dittus –Boelter type correlation for prediction Nusselt number and a Blasius type correlation for prediction of friction factor. These correlations were compared with both experimental results and studies in the literature. Their study showed that friction factor and Nusselt number of micro-finned tube in the range of $3300<Re<22500$ can predict by means of Haaland and Gnielinski correlations, respectively.

Carvanos [6] investigated heat transfer performance of internal spiral and longitudinal finned tubes in turbulent flow in the range of $10000<Re<100000,0,7<Pr<30$ and $0^o<\text{helix angle}<30^o$.The author used Wilson plot technique and Gardner method in order to determine heat transfer performance and fin tube efficiency. According to fin tube efficiency results, tubes having higher helix angle and heat transfer surface area have the best heat transfer performance among 11 test tubes. As another result of the study, he proposed pressure drop correlation which includes effect of helix angle.

Jensen and Vlakancic [7] proposed new correlations for prediction of Nusselt number and friction factor of both high and micro fin tube. They investigated effect of fin geometry to the performance of finned tubes by means of these correlations and compared friction factor and Nusselt number results with Filonenko and Gnielinski correlations for smooth tube, respectively. The correlations are applied to a smooth and 15 finned tubes having different outside diameter, inside diameter fin height, fin thickness and fin helix angle. Their study showed that friction factor and Nusselt number increased with increasing number of fins. As an another result of their study, friction factor and Nusselt number increased with increasing fin height under the same conditions.

Zdaniuk et al. [8] experimentally studied single phase heat transfer characteristic of one smooth tube and eight helically finned tubes having the helix angle of 25°–28°, e/D ratios of 0.0199–0.0327, number of fin between 10-45.They conducted experiments in order to determine fanning friction and Colburn j-factors in the range of between $12000<Re<60000$ by using water as test fluid. They compared fanning friction factor results with Blasius equation and Nusselt number results with Dittus-Boelter equation. They evaluated the performance of the correlations with data of other researchers (Webb and Jensen Vlakancic) and showed average prediction errors between 30% and 40%.

Al Fahed et al. [9] performed an experimental study in order to determine heat transfer coefficients and friction factors of microfinned tube under turbulent flow conditions. Inside and outside heat transfer coefficients were determined by using Wilson method in the study. They produced empirical correlations for prediction of heat transfer and friction factor data. They stated that micro-finned tube heat transfer performance enhancement varied from 1.2 to 1.8 times higher than smooth tube and pressure drop increase changed between 1.3 and 1.8.

Han and Lee [10] conducted experiments related to single phase heat transfer and flow characteristics of micro-fin tubes. They tested four different tubes in order to indicate experimental friction factor and heat transfer coefficients in the Reynolds number range between 3000 and 40000. Heat transfer coefficients and friction factor correlations were produced by mean means of experimental data in the study .Their performance were evaluated with mean square deviation and root mean square deviation which were lower than 6.4%. Their study revealed that performance of tube having smaller spiral angle and higher relative roughness showed better than tube having larger spiral angle and lower relative roughness among the tested tubes. They also stated that heat transfer area increase was an important parameter for efficiency index.

Wang and Rose [11] set up an experimental data for prediction of effective friction factor for single phase flow in horizontal micro-fin tubes. They used six correlations belonging to experimental studies given in the literature (Wang et al. [2], Carvanos [6], Jensen and Vlakancic [7], Webb et al. [12] , Ravigururajan and Bergles [13] and Cavallini et al.[14]) containing a wide range of tube and fin geometric variables (inside diameter at the fin root between 6.46 and 24.13 mm, fin height between 0.13 and 0.47 mm, fin pitch between 0.32 and 1.15 mm and helix angle between 17 and 45 degrees) and Reynolds number. They calculated mean square deviation and root mean square deviation of each correlation for different Reynolds number. They stated that correlation of Jensen and Vlakancic presents the database the best.

Naphon and Sriromruln [15] investigated pressure drop and heat transfer characteristics of micro-fin tube both with and without coiled wire insert. They used smooth tube, micro-fin tube with coiled insert and micro-fin tube without coiled insert in the experiments and studied effect of inlet hot water temperature, inlet cold water temperature, hot water mass flow rate, cold water mass flow rate to the performance of double pipe heat exchanger performance. According to experimental results, they found that the coiled wire has a significant effect on the enhancement of heat transfer but the tube with coiled wire insert had higher friction factor results.

Brognaux et al. [16] studied single-phase heat transfer and friction factor of single and cross-grooved micro-fin tubes experimentally. They aimed to define Prandtl number dependency and the effect of surface geometry on the Prandtl number dependence. They stated that cross-grooved tube had higher performance than the best single grooved tube. Their study showed that usage of micro-fin tubes instead of smooth one provided enhancement ratio up to 95%.However, micro-fin tubes had higher friction factors between 35% and 80% when they compared with smooth tube.

1.2 Aim of Thesis

It is well known that usage of microfin tube improves heat transfer but increases pressure drop. This study is aimed to determine single phase pressure drop characteristics of smooth and microfinned tube in a double pipe heat exchanger for different working conditions experimentally.

Table 1.1 Summary of studies about single-phase flow in micro-fin tube

Researcher	Year	Fluid	Reynolds Number	Number of tested tubes
Wang et al. [2]	1996	Water	2500<Re<40000	8
Copettiet al. [3]	2004	Water	2000<Re<20000	2
Wei et al. [4]	2007	Water&Oil	2500<Re<90000	1
Siddique and Alhazmy [5]	2008	Water	3300<Re<22500	1
Carvanos [6]	1980	Water	10000<Re<100000	14
Jensen and Vlakancic [7]	1999	Water&EG	10000<Re<100000	16
Zdaniuket al. [8]	2008	Water	12000<Re<60000	9
Al Fahedet al. [9]	1993	Water	10000<Re<30000	2
Han and Lee [10]	2005	Water	3000<Re<40000	4
Wang and Rose [11]	2004	Water&R11&EG	2000<Re<163000	21
Naphon and Sriromruln [15]	2006	Water	8000<Re<25000	2
Brognaux et al. [16]	1997	Water	2500<Re<50000	5

In order to determine pressure drop characteristic of smooth and microfin tube, pressure drop, friction factor coefficient and wall shear stress are calculated by using water test fluid. Blasius type friction factor equations are produced by using experimental results. Experimental results are compared with results given in the literature.

1.3 Hypothesis

Heat transfer enhancement has become more important issue over the years. Microfin tubes play important role in heat transfer enhancement applications. Many researchers have focused on two phase heat transfer characteristic of microfin tubes but single phase heat transfer characteristic of microfin tubes are not well studied. In the present paper, pressure drop by means of microfin tube in single phase flow will be discussed. It is expected from this study the usage of microfin tube will result in pressure drop and degree of pressure drop will be determined.

CHAPTER 2

BASIC CONCEPTS

2.1 Definition of Flow Types

Flow in a tube can be laminar or turbulent, depending on the flow conditions. Fluid flow is streamlined and thus laminar at low velocities, but turns turbulent as the velocity is increased beyond a critical value. Transition from laminar to turbulent flow does not occur suddenly; rather, it occurs over some range of velocity where the flow fluctuates between laminar and turbulent flows before it becomes fully turbulent. Most pipe flows encountered in practice are turbulent. Laminar flow is encountered when highly viscous fluids such as oils flow in small diameter tubes or narrow passages.

For flow in a circular tube, the Reynolds number is defined as follows:

$$\mathrm{Re} = \frac{\rho . V_m . D}{\mu} \qquad (2.1)$$

where

ρ density of fluid (kg/m3)

V_m mean fluid velocity (m/s)

D tube diameter (m)

M dynamic viscosity (kg/m.s)

It certainly desirable to have precise values of Reynolds number for laminar, transitional and turbulent flows but this is not the case in practice. This is because the transition from laminar to turbulent flow also depends on the degree of disturbance of the flow by surface roughness, pipe vibrations and the fluctuations in the flow. Under most practical conditions, flow in a tube is laminar for Re<2300, turbulent for Re>10000 and transitional between this numbers [17].

Table 2.1 Definition of flow types according to Reynolds number

Reynolds number	Flow Type
Re<2300	Laminar flow
2300<Re<10000	Transitional flow
Re>10000	Turbulent flow

2.2Pressure Drop in Tubes

A quantity of interest in the analysis of tube flow is the pressure drop ΔP since it is directly related to the power requirements of the pump to maintain flow. We note that dP/dx=constant and integrate it from x=0 where the pressure is P_1 to x=L where the pressure is P_2.We get

$$\frac{dP}{dx} = \frac{P_2 - P_1}{L} = -\frac{\Delta P}{L} \qquad (2.2)$$

Note that in fluid mechanics, the pressure drop ΔP is a positive quantity and is defined as $\Delta P = P_1 - P_2$.

For laminar flow, pressure drop can be expressed as follows:

$$\Delta P = \frac{8.\mu.L.V_m}{R^2} = \frac{32.\mu.L.V_m}{D^2} \qquad (2.3)$$

In practice, it is found convenient to express the pressure drop for all types of internal flows (laminar or turbulent flows, circular or noncircular tubes, smooth or rough surfaces) as follows:

$$\Delta P = f.\frac{L}{D}.\frac{\rho V_m{}^2}{2} \qquad (2.4)$$

Where the dimensionless quantity f is the friction factor (also called the Darcy friction factor after French engineer Henry Darcy who first studied experimentally the effects of roughness on tube resistance).

Equation (2.4) gives the pressure drop for a flow section of length L provided that,

- The flow section is horizontal so that there are no hydrostatic or gravity effects.
- The flow section does not involve any work device such as a pump or turbine since they change the fluid pressure
- The cross sectional area of the flow section is constant and thus the mean flow velocity is constant

2.3 Friction Factor for Smooth And Microfin Tubes

Setting Equations (2.3) and (2.4) equal to each other and solving for f gives the friction factor for fully developed laminar flow in a circular tube as follows:

$$f = \frac{64.\mu^2}{\rho.D.V_m} = \frac{64}{\text{Re}} \tag{2.5}$$

This equation shows that in laminar flow, friction factor is function of the Reynolds number only and is independent of the roughness of the tube surface [17]. For smooth and microfin tubes, the friction factor in turbulent flow can be determined from the correlations given in the Table 2.2 and 2.3 respectively.

Table 2.2 Friction factor correlations for smooth tube

Researcher	Correlation
Blasius [18]	$f = 0.316\ \text{Re}^{-1/4}$
Moody [19]	$f = 0.184\ \text{Re}^{-1/5}$
Petukhov [20]	$f = (0,79\ \ln \text{Re} - 1,64)^{-2}$
Colebrook [21]	$f = (1.8 \log \frac{\text{Re}}{6.9})^{-2}$

Table 2.3 Friction factor correlations for microfin tubes

Researcher	**Correlation**
C. C. Wang et al.[2]	$e^{+} = \left(\frac{e}{D_i}\right)\mathrm{Re}\sqrt{\frac{f}{2}}$ where for $e^{+}<23$ $e^{+} = 0{,}1407 + 0{,}093675 X_f + 0{,}58464/\ln(X_f)$ for $e^{+}>23$ $e^{+} = 0{,}07313 + 0{,}09511 X_f \; for h+ > 23$ $X_f = \mathrm{Re}\left(\frac{e}{D_i+\lambda}\right)\frac{n^{0,25}}{(\cos\alpha)^{0,5}}$
Siddique and Alhazmy [5]	$f = 0{,}907\ \mathrm{Re}^{-0,286}$
Carvanos [6]	$f = 0{,}046\,\mathrm{Re}^{-0,2}\left(\frac{d}{d_h}\right)^{1,2}\left(\frac{A}{A_n}\right)^{0,5}(\sec\alpha)^{0,75}$
Jensen and Vlakancic [7]	$\frac{f}{f_{Fi(smooth)}} = \left(\frac{l_c}{d}\right)^{-1,25}\left(\frac{A_n}{A}\right)^{1,75} - \left(\frac{0{,}0151}{f_{Fi}}\right)*$ $\left\{\left(\frac{l_c}{d}\right)^{-1,25}\left(\frac{A_n}{A}\right)^{1,75} - 1\right\}\exp\left(-\frac{\mathrm{Re}}{6780}\right)$ $\frac{l_c}{d} = 1 - 1{,}577\left(\frac{n\sin\gamma}{\pi}\right)^{0,64}\left(\frac{2h}{d}\right)0{,}53\left\{\left(\frac{\pi}{n} - \frac{s}{d}\right)\cos\alpha\right\}^{0,28}$ $f_{Fi} = (1{,}58\ln\mathrm{Re} - 3{,}28)^{-2}$ $s = \frac{p}{\cos\gamma} - \frac{\pi}{4}(d^2 - d_e^{\,2})/(nh)$
Zdaniuk et al. [8]	$f = 0{,}128\ \mathrm{Re}^{-0,305}\, n^{0,235}(e/D)^{0,319}\alpha^{0,397}$

Table 2.3 Friction factor correlations for microfin tubes (Continued)

Researcher	**Correlation**
Al Fahed et al. [9]	$f = 0{,}9978\ \mathrm{Re}^{-0{,}2943}$
Webb et al. [12]	$\sqrt{\frac{2}{f_e}} = B(h^+) - 2{,}5\ln(2h/d) - 3{,}75$ $B(h^+) = 4{,}762\,(h^+)^{0{,}2138}\, n^{-0{,}1096}\, \alpha^{-0{,}297}$ $h^+ = \left(\frac{h}{d}\right)\mathrm{Re}\sqrt{\frac{f_e}{2}}$ or $f = 0{,}128\,\mathrm{Re}^{-0{,}305}\, n^{0{,}235}(e/D)^{0{,}319}\alpha^{0{,}397}$
Ravigururajan and Bergles [13]	$\frac{f}{f_{Fi}} = \left\{1 + \left[29{,}1\,\mathrm{Re}^{a1}(h/d)^{a2}(p/d)^{a3}(\alpha/90)^{a4}(1+1{,}47\cos\theta\right]^{15/16}\right\}^{16/15}$ where $f_{Fi} = (1{,}58\ \ln\ \mathrm{Re} - 3{,}28)^{-2}$ $a1 = 0{,}67 - 0{,}06\,p/d - 0{,}49\alpha/90$ $a2 = 1{,}37 - 0{,}157\,p/d$ $a3 = -1{,}66.10^{-6}\,\mathrm{Re} - 0{,}33\alpha/90$ $a4 = 4{,}59 + 4{,}11.10^{-6}\,\mathrm{Re} - 0{,}15\,p/d$
Haaland[22]	$f = \frac{0{,}3086}{\left\{\log\left[\frac{6{,}9}{\mathrm{Re}} + \left(\frac{\varepsilon}{3{,}7D}\right)^{1{,}11}\right]\right\}^2}$

CHAPTER 3

EXPERIMENTAL STUDY

3.1 Experimental Setup

The experimental set up which allows conducting pressure drop measurement of tube was installed and its schematic representation is given Figure 3.1. By means of experiment set up, single phase pressure drop characteristics of smooth and micro-fin tubes were determined for different flow conditions. In the experimental study, as inner tube of double pipe heat exchanger smooth and microfin were used.

Basic working principle of experimental set up can be summarized as follows:

- Water (working fluid) is circulated by means of frequency controlled pump.
- Hot water is heated in the hot water tank and sent to plate heat exchanger in order to transfer its heat to working fluid.
- In the plate exchanger, water is heated until required temperature.
- Cold water is cooled in the cold water tank and sent to test section in order heat reject from working fluid.
- Experiments are conducted for 10 different mass flow rate of working fluid in the range between 0,02 and 0,1 kg/s.
- In the steady state conditions, temperature, pressure and flow rate parameters are recorded.

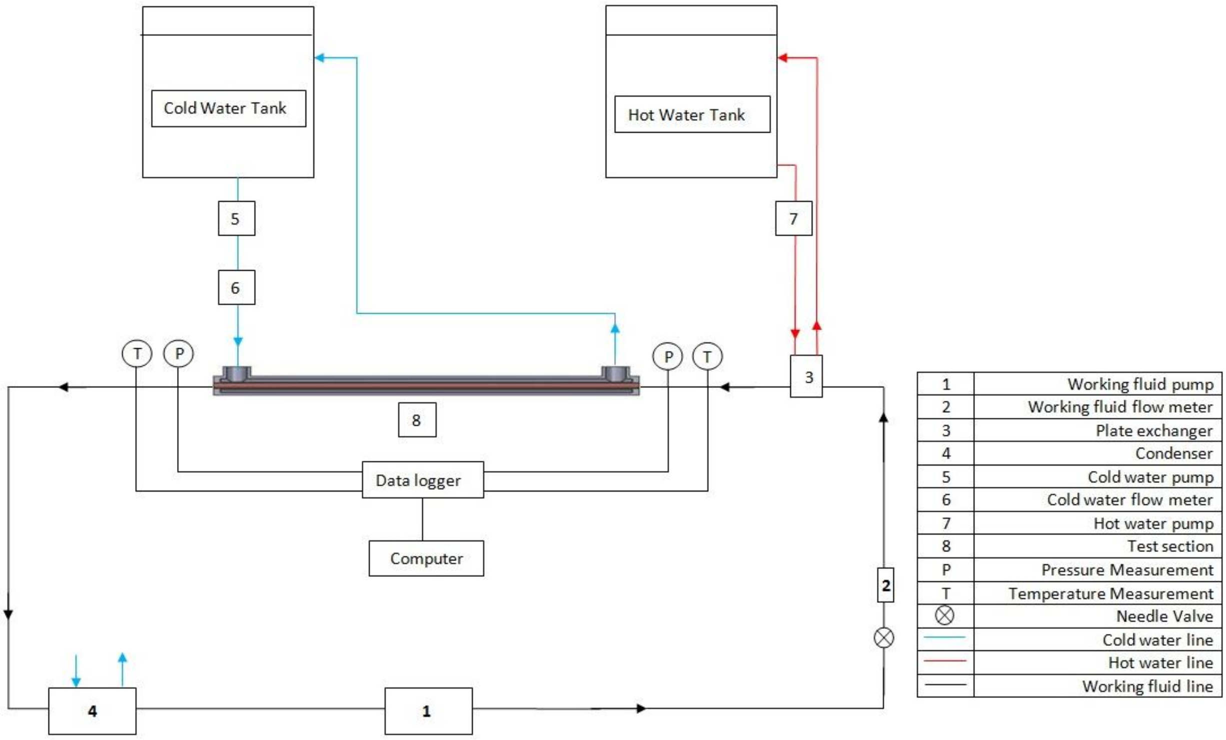

Figure 3.1 Schematic representation of experimental setup

Figure 3.2 Picture of experimental setup

Figure 3.3 Back side picture of experimental setup

3.2 Test Section

In the experiments two test sections (double pipe heat exchangers) are used. One of them is test section (double pipe heat exchangers) which is comprised of a copper inside smooth tube and plastic shell tube. Other one is test section (double pipe heat exchangers) which is comprised of an internally microfinned copper inside tube and plastic shell tube. Internally microfinned tube is provided from Wieland Copper Products Company [23] and shown Figure 3.2. Test sections are isolated in order to avoid heat loss. Temperature and pressure measurement instruments are located both inlet and outlet of test section and schematic representation of test sections is given Figure 3.3.

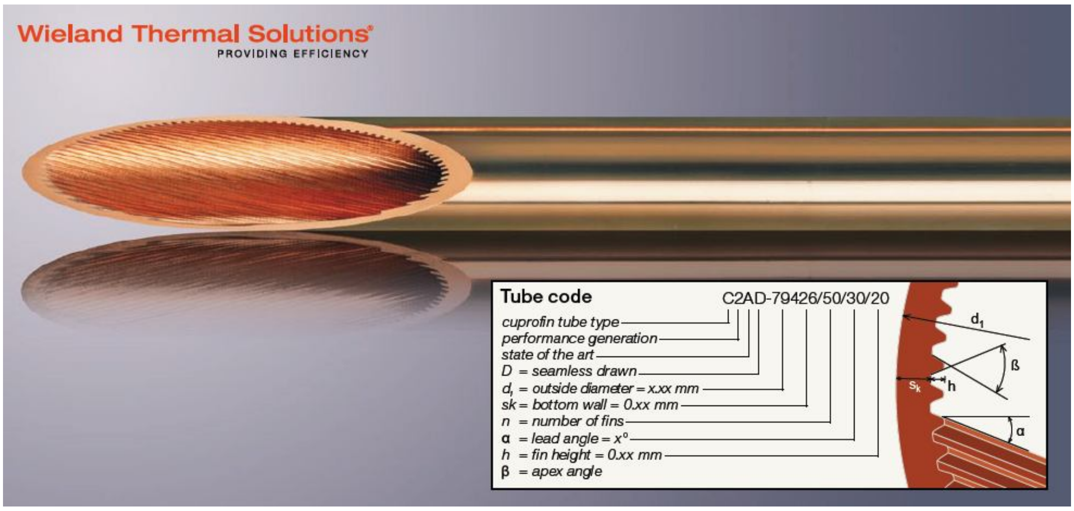

Figure 3.4 Microfin tube used in the study

Figure 3.5 Schematic representation of horizontal test section

Figure 3.6Assembled heat exchanger (Test section)

Table 3.1 Geometrical parameters of tubes used in the experiments

Parameter	Unit	Smooth Tube 1	Smooth Tube 2	Micro-fin Tube
Length (L)	mm	1100	1100	1100
Outside diameter (D_o)	mm	8	10	8
Inside diameter (D_i)	mm	6	8	7,48
Thickness (t)	mm	1	1	0,26
Fin Height (e)	mm	-	-	0,22
Fin pitch (p)	mm			0,34
Helix angle (α)	o	-	-	35
Number of fins (n)	-	-	-	65
e/D	-	-	-	0,027

3.3 Experimental Setup Equipments

Table 3.2 List of measurement devices used in the experimental study

Measurement Device	Property	Number
Temperature measurement RTD (Pt100)	Diameter: 3 mm Length : 50 mm	4
Differential Pressure Transmitter	Accuracy : 0.03% Current Output :4-20 mA Pressure Range:0-1250mbar	1

Table 3.2 List of measurement devices used in the experimental study (Continued)

Measurement Device	Property	Number
Hot Water Tank Pump	H min : 5 m H max :40 m Q min: 0,2 m^3/h Q max: 1,9 m^3/h	1
Test Section Line Cold Water Pump	H min : 5 m H max :40 m Q min: 0,2 m^3/h Q max: 1,9 m^3/h	1
Condenser Cold Water Pump	H min : 5 m H max : 40 m Q min: 5 l/min Q max: 40 l/min	1
Water Tank	0.25 m^3 water capacity Heating and cooling ability	2
Data logger	VTİ EX 1262 Two standard plug-in module slots plus 6½ digit DMM Channel:64	1
Valve	On/off type	5
Needle Valve	Regulator for flow meter	2

Table 3.2 List of measurement devices used in the experimental study (Continued)

Measurement Device	Property	Number
Water (Working fluid) flow meter	Accuracy :2,5% Current Output:4-20 mA Measuring Range:0,1-25 l/min	2
Cold water flow meter	Accuracy : 0.5% Current Output (2 wire): 4-20 mA 2x4 digit led display	1
Plate heat exchanger	BP 10-14 Plate Type	1

3.4Data Recording

For each test section 4 count Pt100, 2 pressure transmitter, 1 differential pressure transmitter and 2 flow meters are connected data logger which is connected to computer. By means of data logger measurement are recorded to computer. In each experiment, data is taken along 5 minutes and exported to Excel file. Average of the data is calculated in the Excel file and taken into consideration.

3.5 Experimental Setup Photos

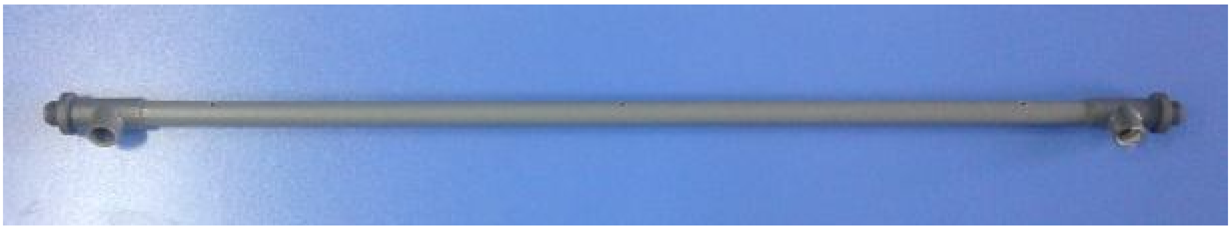

Figure 3.7 Shell of heat exchanger (test section)

Figure 3.8 Assembled heat exchanger (test section) on the experimental setup

Figure 3.9 Data logger

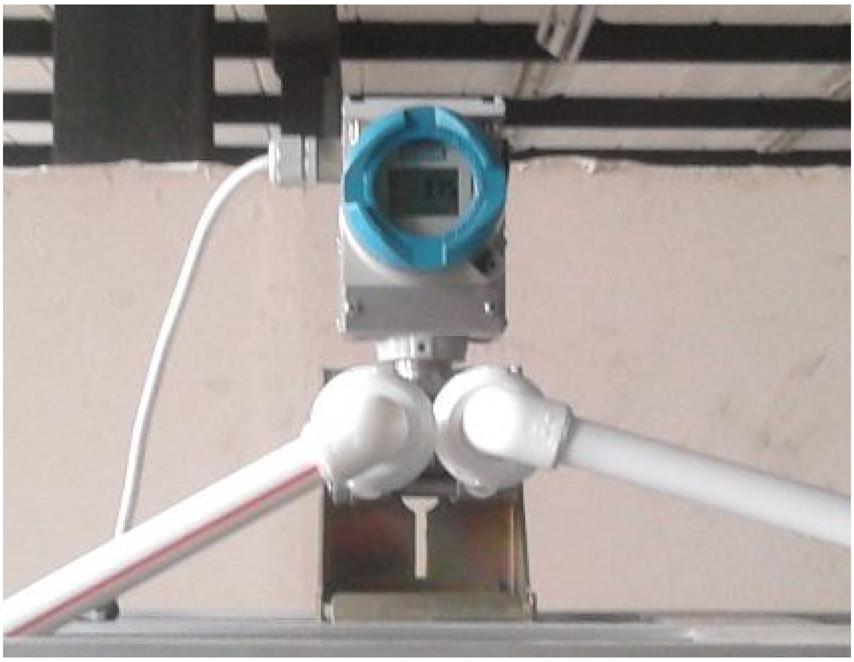

Figure 3.10Differential pressure transmitter

Figure 3.11Pt100 temperature sensor

Figure 3.12Flow meter and frequency controller of pump

Figure 3.13Hot and cold water production tanks

Figure3.14Plate heat exchanger

CHAPTER 4

CALCULATION PROCEDURE

4.1 Smooth Tube

Pressure drop is calculated in two ways. One way is experimental measurement; other is by means of equation given below:

$$\Delta P = f.\frac{L}{D}.\frac{\rho.V_m{}^2}{2} \tag{4.1}$$

where

ΔP pressure drop (kPa)

f friction factor

L tube length (m)

D tube inner diameter (m)

ρ density of fluid (kg/m^3)

V_m mean velocity of fluid (m/s)

Friction factors are calculated according to experiment, Blasius [18] and Petukhov [20] Equations by using equations given below:

$$f_{experiment} = \frac{\Delta P_{experiment}.D.2}{L.\rho.V_m{}^2} \tag{4.2}$$

$$f_{blasius} = 0.316\,\mathrm{Re}^{-1/4} \tag{4.3}$$

$$f_{petukhov} = (0.79 \ln \mathrm{Re} - 1.64)^{-2} \quad (4.4)$$

According to Blasius friction factor equation pressure drop is calculated as follows:

$$\Delta P_{blasius} = f_{blasius} \cdot \frac{L}{D} \cdot \frac{\rho . V_m{}^2}{2} \quad (4.5)$$

According to Petukhov friction factor equation pressure drop is calculated as follows:

$$\Delta P_{petukhov} = f_{petukhov} \cdot \frac{L}{D} \cdot \frac{\rho . V_m{}^2}{2} \quad (4.6)$$

Wall shear stresses are calculated according to experiment, Blasius and Petukhov Equations by using equations given below:

$$\tau_{\exp eriment} = \frac{f_{\exp eriment} \cdot \rho . V_m}{8} \quad (4.7)$$

$$\tau_{blasius} = \frac{f_{blasius} \cdot \rho . V_m}{8} \quad (4.8)$$

$$\tau_{petukhov} = \frac{f_{petukhov} \cdot \rho . V_m}{8} \quad (4.9)$$

4.1.1 Smooth Tube Correlation Development

New friction factor correlation is developed by using experimental data and graphical program. Curve Expert program [24] is used in order to get new friction factor correlations. In the program Quadratic and Power models are selected and suitable curve is obtained. The R^2 value of fit data of correlation for quadratic model is 0,99287 showing that the correlation model explains 99,287% of variability in the data. The R^2 value of fit data of correlation for power model is 0,99292 showing that the correlation model explains 99,292% of variability in the data. Data which are used in the correlation development is given Table 4.1

Table 4.1 Data used in the development of correlation 1 and 2

Data number	(Re) x value	(f) y value
1	7175,028	0,038664
2	9700,458	0,036646
3	12709,16	0,035062
4	14851,65	0,033201
5	17988,91	0,031956
6	21108,08	0,030982
7	23288,92	0,030067
8	26186,71	0,029677
9	28860,94	0,028855
10	31775,32	0,028872
11	9494,702	0,037384
12	12917,52	0,035063
13	17134,87	0,033412
14	20175,77	0,031427
15	24292,01	0,029638
16	28722,57	0,02867
17	31635,49	0,027963
18	35481,31	0,027844
19	39218,29	0,027813
20	43131,42	0,026453

4.1.1.1 Proposed Correlation 1 for 6/8 mm Smooth Tube 1

Developed correlation according to Quadratic model as a result of curve fitting process is given below:

Result of curve fitting process produced correlation is given below:

$$y = a + bx + cx^2 \tag{4.10}$$

Where coefficients

a is equal to 0.043597428

b is equal to $-7.9170701.10^{-7}$

c is equal to $9.5654334.10^{-12}$

y is friction factor

x is Reynolds number

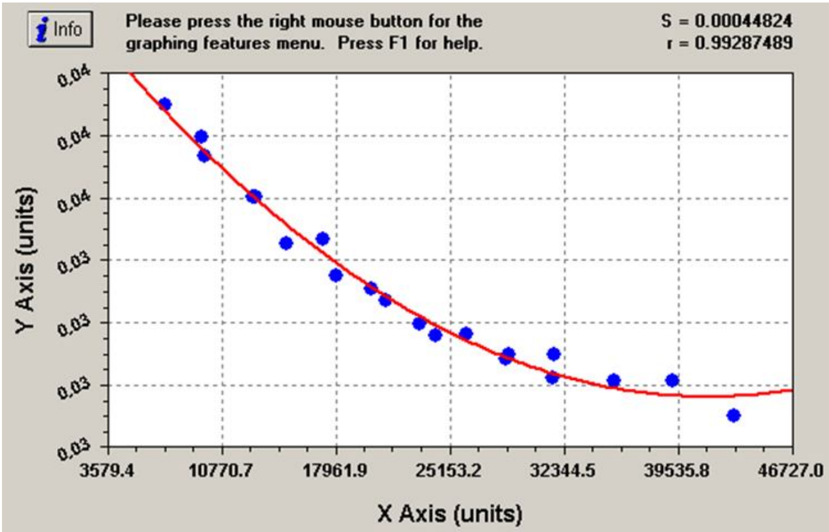

Figure 4.1Experimental data and curve fitting for Correlation 1

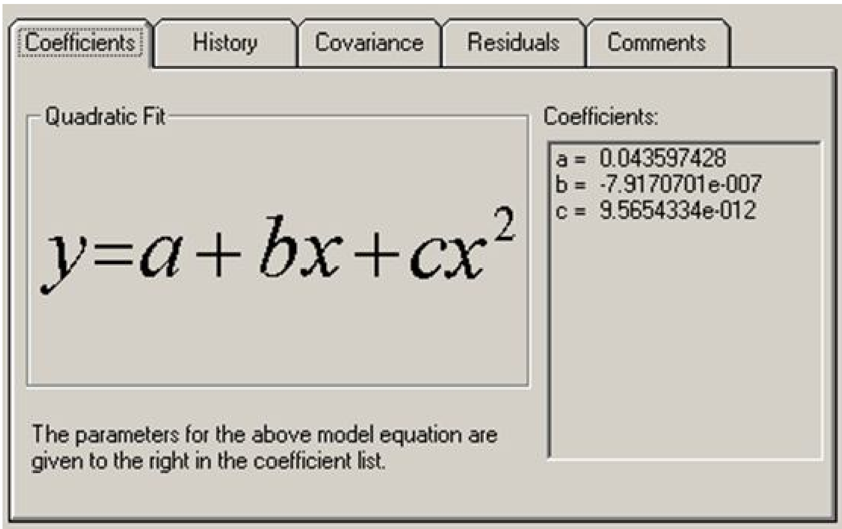

Figure 4.2Quadratic model information for Correlation 1

Developed correlation for friction factor:

$$f_{correlation1} = 0,043597428 - 7.9170701.10^{-7}.\mathrm{Re} + 9.5654334.10^{-12}.\mathrm{Re}^2 \qquad (4.11)$$

Developed correlation for pressure drop:

$$\Delta P_{correlation1} = f_{correlation1}\cdot\frac{L}{D}\cdot\frac{\rho.V_m^{2}}{2} \quad (4.12)$$

4.1.1.2 Proposed Correlation 2 for 6/8 mm Smooth Tube 1

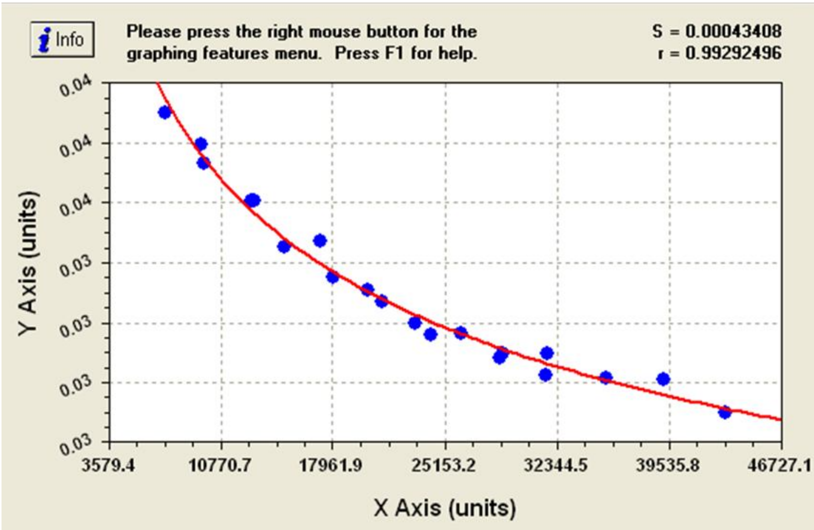

Figure 4.3 Experimental data and curve fitting for Correlation 2

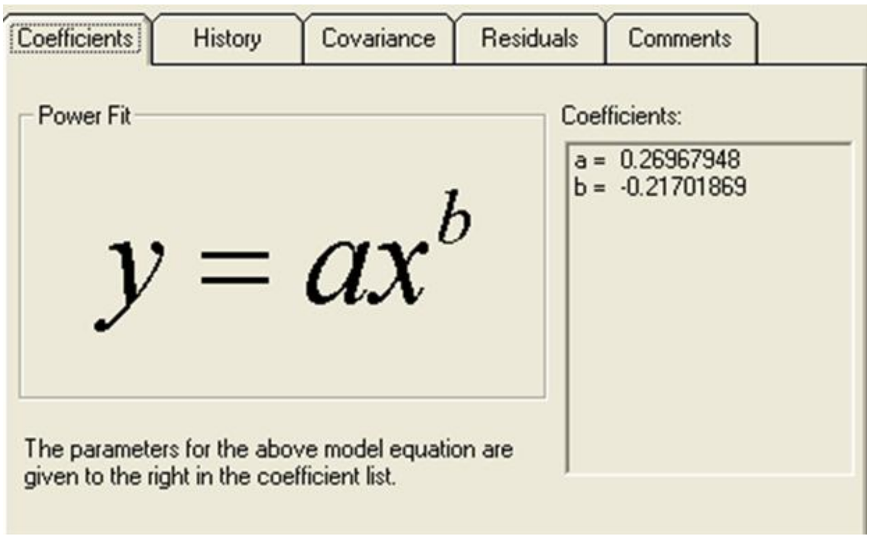

Figure4.4 Power model information for Correlation 2

Developed correlation according to Power model as a result of curve fitting process is given below:

Result of curve fitting process produced correlation is given below:

$$y = a.X^{b} \quad (4.13)$$

Where coefficients

a is equal to0.26967948

b is equal to -0.21701869

y is friction factor

x is Reynolds number

Developed correlation for friction factor:

$$f_{correlation2} = 0{,}26967948 \,.\, \mathrm{Re}^{-0{,}21701869} \qquad (4.14)$$

Developed correlation for pressure drop:

$$\Delta P_{correlation2} = f_{correlation2} \cdot \frac{L}{D} \cdot \frac{\rho . V_m{}^2}{2} \qquad (4.15)$$

4.1.1.3 Proposed Correlation 3 for 8/10 mm Smooth Tube 2

Table 4.2 Data used in the development of correlation 3

Data number	(Re) x value	(f) y value
1	5445,982	0,058321
2	7274,276	0,047342
3	9531,867	0,04159
4	11138,74	0,03801
5	13296,15	0,036026
6	15635,62	0,033255
7	17466,69	0,032505
8	19640,03	0,031895
9	21645,7	0,030398
10	23831,49	0,02925

Developed correlation according to Power model as a result of curve fitting process is given below:

Result of curve fitting process produced correlation is given below:

$$y = a.X^b \qquad (4.16)$$

Where coefficients

a is equal to 2.79385684806

b is equal to -0.456896082909

y is friction factor

x is Reynolds number

Developed correlation for friction factor:

$$f_{correlation3} = 2.79385684806.\mathrm{Re}^{-0.456896082909} \tag{4.17}$$

Developed correlation for pressure drop:

$$\Delta P_{correlation3} = f_{correlation3}.\frac{L}{D}.\frac{\rho.V_m^{\ 2}}{2} \tag{4.18}$$

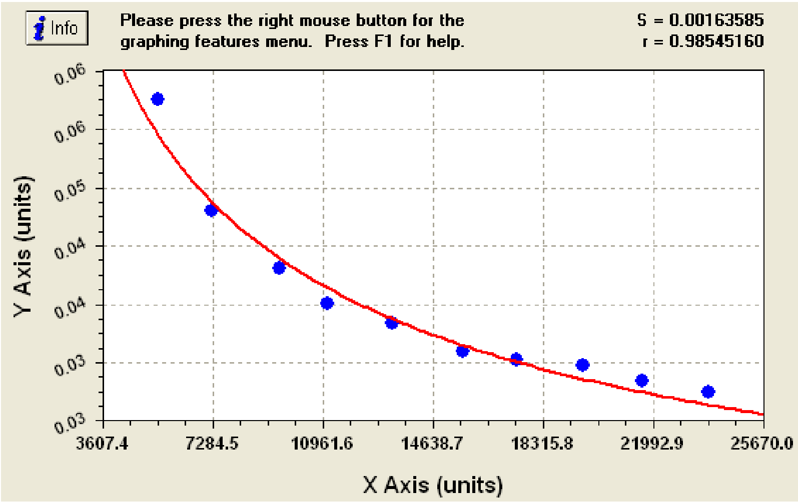

Figure 4.5 Experimental data and curve fitting for Correlation 3

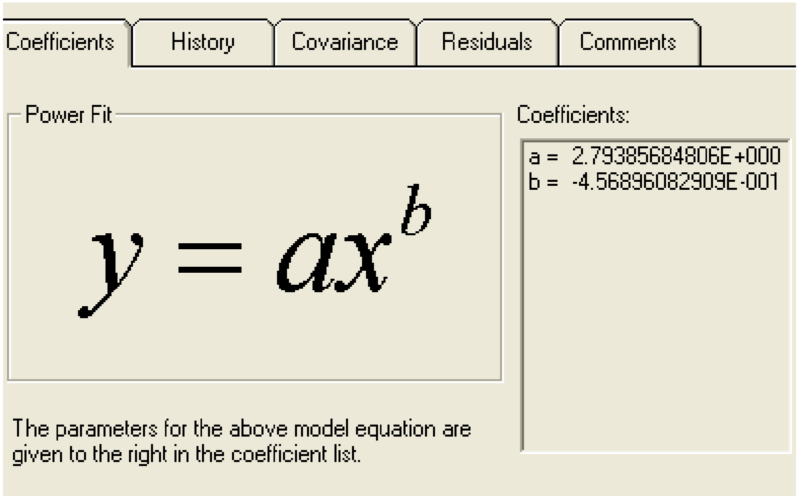

Figure 4.6 Power model information for Correlation 3

4.1.1.4 Proposed Correlation 4 Simulated Smooth Tube 3

This correlation is developed by using 6/8 mm and 8/10 mm tube data in order to predict smooth tube3 having 7.48 mm inside diameter.

Table 4.3 Data used in the development of correlation 4

Data number	(Re) x value	(f) y value
1	5445,982	0,058321
2	7274,276	0,047342
3	9531,867	0,04159
4	11138,74	0,03801
5	13296,15	0,036026
6	15635,62	0,033255
7	17466,69	0,032505
8	19640,03	0,031895
9	21645,7	0,030398
10	23831,49	0,02925
11	7175,028	0,038664
12	9700,458	0,036646
13	12709,16	0,035062
14	14851,65	0,033201
15	17988,91	0,031956
16	21108,08	0,030982
17	23288,92	0,030067
18	26186,71	0,029677
19	28860,94	0,028855
20	31775,32	0,028872

Developed correlation according to Saturation Growth-Rate Model as a result of curve fitting process is given below:

Result of curve fitting process produced correlation is given below:

$$y = \frac{a.X}{b + x} \tag{4.19}$$

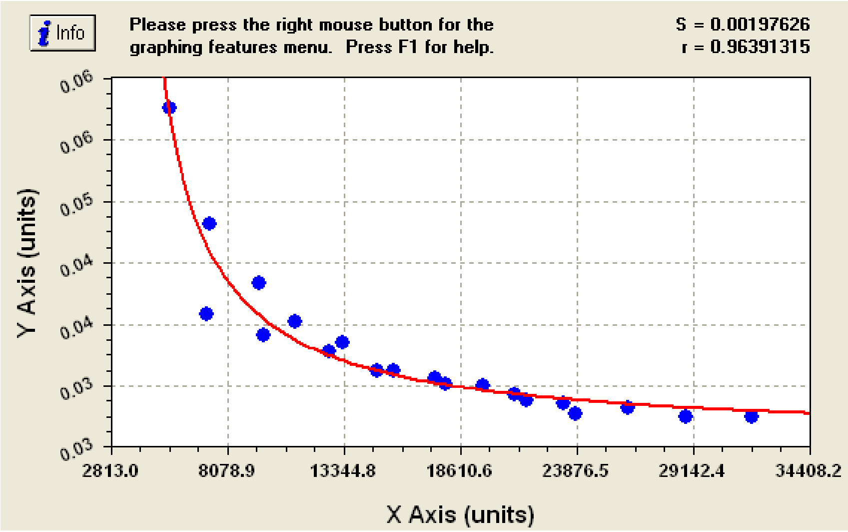

Figure 4.7 Experimental data and curve fitting for Correlation 4

where coefficients

a is equal to 2.67337088609E-002

b is equal to -2.91512922675E+003

y is friction factor

x is Reynolds number

Developed correlation for friction factor:

$$f_{correlation4} = \frac{0,02673.\text{Re}}{-2915 + \text{Re}} \tag{4.20}$$

Developed correlation for pressure drop:

$$\Delta P_{correlation4} = f_{correlation4} \cdot \frac{L}{D} \cdot \frac{\rho . V_m{}^2}{2} \tag{4.21}$$

4.2 Microfin Tube

Pressure drop is calculated in two ways. One way is experimental measurement; other is by means of equation given below:

$$\Delta P = f.\frac{L}{D_e}.\frac{\rho.V_m^{\ 2}}{2} \quad (4.22)$$

where

ΔP pressure drop (kPa)

f friction factor

L tube length (m)

D_e equivalent inside diameter (m)

ρ density of fluid (kg/m^3)

V_m mean velocity of fluid (m/s)

In the Eq. (4.22) friction factor is calculated by using friction factor equations given in the literature as follows:

4.2.1 Wang et al. Equation [2]

Equation for friction factor according to Wang et al. [2] is given below:

$$e^{+} = \left(\frac{e}{D_i}\right)\mathrm{Re}\sqrt{\frac{f_{wang}}{2}} \quad (4.23)$$

where

For $e^{+}<23$

$$e^{+} = 0,1407 + 0,093675X_f + 0,58464 / \ln(X_f) \quad (4.24)$$

For $e^{+}>23$

$$e^{+} = 0,07313 + 0,09511X_f \quad (4.25)$$

$$X_f = \mathrm{Re}\left(\frac{e}{Di+\lambda}\right)\frac{n^{0,25}}{(\cos\alpha)^{0,5}} \quad (4.26)$$

λ is assumed 0,005 in the Eq. (4.26).

Pressure drop is calculated as follows:

$$\Delta P_{wang} = f_{wang}.\frac{L}{D_e}.\frac{\rho.V_m^{\ 2}}{2} \quad (4.27)$$

4.2.2 Siddique and Alhazmy Equation [5]

Equation for friction factor according to Siddique and Alhazmy [5] is given below:

$$f_{siddique} = 0,907\ \mathrm{Re}^{-0,286} \quad (4.28)$$

Pressure drop is calculated as follows:

$$\Delta P_{siddique} = f_{siddique} \cdot \frac{L}{D_e} \cdot \frac{\rho . V_m^{\;2}}{2} \qquad (4.29)$$

4.2.3 Jensen and Vlakancic Equation [7]

Equation for friction factor according to Jensen and Vlakancic [7] is given below:

$$\frac{f_{jensen}}{f_{F\dot{I}(smooth)}} = \left(\frac{l_c}{d}\right)^{-1,25}\left(\frac{A_n}{A}\right)^{1,75} - \left(\frac{0{,}0151}{f_{Fi}}\right) * \left\{\left(\frac{l_c}{d}\right)^{-1,25}\left(\frac{A_n}{A}\right)^{1,75} - 1\right\} \exp\left(-\frac{\text{Re}}{6780}\right) \qquad (4.30)$$

$$\frac{l_c}{d} = 1 - 1{,}577\left(\frac{n \sin\gamma}{\pi}\right)^{0,64}\left(\frac{2h}{d}\right) 0{,}53 \left\{\left(\frac{\pi}{n} - \frac{s}{d}\right)\cos\alpha\right\}^{0,28} \qquad (4.31)$$

$$f_{F\dot{I}} = (1{,}58 \ln \text{Re} - 3{,}28)^{-2} \qquad (4.32)$$

$$s = \frac{p}{\cos\alpha} - \frac{\pi}{4}(d^2 - d_e^{\;2})/(nh) \qquad (4.33)$$

Pressure drop is calculated as follows:

$$\Delta P_{jensen} = f_{jensen} \cdot \frac{L}{D_e} \cdot \frac{\rho . V_m^{\;2}}{2} \qquad (4.34)$$

4.2.4 Zdaniuk et al. Equation [8]

Equation for friction factor according to Zdaniuk et al [8] is given below:

$$f_{zdaniuk} = 0{,}128\,\text{Re}^{-0,305}\,N_s^{\;0,235}(e/D)^{0,319}\alpha^{0,397} \qquad (4.35)$$

Pressure drop is calculated as follows:

$$\Delta P_{zdaniuk} = f_{zdaniuk} \cdot \frac{L}{D_e} \cdot \frac{\rho . V_m^{\;2}}{2} \qquad (4.36)$$

4.2.5 Al Fahed et al. Equation [9]

Equation for friction factor according to Al Fahed et al. [9] is given below:

$$f_{alfahed} = 0{,}9978\ \text{Re}^{-0,2943} \qquad (4.37)$$

Pressure drop is calculated as follows:

$$\Delta P_{alfahed} = f_{alfahed} \cdot \frac{L}{D_e} \cdot \frac{\rho . V_m^{\;2}}{2} \qquad (4.38)$$

4.2.6 Webb et al. Equation [12]

Equation for friction factor according to Webb et al. [12] is given below:

$$\sqrt{\frac{2}{f_{webb}}} = B(h^{+}) - 2{,}5\ln(2h/d) - 3{,}75 \tag{4.39}$$

$$B(h^{+}) = 4{,}762\,(h^{+})^{0{,}2138}\,n^{-0{,}1096}\,\gamma^{-0{,}297} \tag{4.40}$$

$$h^{+} = \left(\frac{h}{d}\right)\mathrm{Re}\sqrt{\frac{f_{webb}}{2}} \tag{4.41}$$

or

$$f_{webb} = 0{,}128\,\mathrm{Re}^{-0{,}305}\,n^{\,0{,}235}(e/D)^{0{,}319}\alpha^{0{,}397} \tag{4.42}$$

Pressure drop is calculated as follows:

$$\Delta P_{webb} = f_{webb}\cdot\frac{L}{D_e}.\frac{\rho.V_m{}^2}{2} \tag{4.43}$$

4.2.7 Haaland Equation [22]

Equation for friction factor according to Haaland [22] is given below:

$$f_{Haaland} = \frac{0{,}3086}{\left\{\log\left[\frac{6{,}9}{\mathrm{Re}} + \left(\frac{\varepsilon}{3{,}7D}\right)^{1{,}11}\right]\right\}^{2}} \tag{4.44}$$

Pressure drop is calculated as follows:

$$\Delta P_{Haaland} = f_{Haaland}\cdot\frac{L}{D_e}.\frac{\rho.V_m{}^2}{2} \tag{4.45}$$

4.2.8 Microfin Tube Correlation Development

New friction factor correlation for microfin tube is developed by using experimental data and graphical program. Curve Expert program is used in order to get new friction factor correlation. In the program Power model is selected and suitable curve is obtained. The R^2 value of fit data of correlation for power model is 0,98661236 showing that the correlation model explains 98,661% of variability in the data. Data which are used in the correlation development is given Table 4.2

Table4.4Data used in the microfin correlation development

Data number	(Re) X value	(f) Y value
1	5755.370	0.086243
2	7697.895	0.080105
3	10194.510	0.074142
4	11913.086	0.071082
5	14429.609	0.066570
6	16931.617	0.065478
7	18680.956	0.066650
8	21005.379	0.063833
9	23150.483	0.063833
10	25488.222	0.060448
11	7616.071	0.081871
12	10361.650	0.074923
13	13744.546	0.070337
14	16183.770	0.066531
15	19485.573	0.063569
16	23039.493	0.062193
17	25376.060	0.059648
18	28460.940	0.060742
19	31458.520	0.060659
20	34597.396	0.056244

4.2.8.1 Proposed Correlation 5

Developed correlation according to Power model as a result of curve fitting process is given below:

Result of curve fitting process produced correlation is given below:

$$y = a.x^{b} \tag{4.46}$$

Where coefficients

a =0.60577736463

b =-0.226451741367

y is friction factor

x is Reynolds number

Developed correlation for friction factor:

$$f_{correlation5} = 0,60577736463 . \mathrm{Re}^{-0,226451741367} \tag{4.47}$$

Developed correlation for pressure drop:

$$\Delta P_{correlation5} = f_{correlation5} . \frac{L}{D_e} . \frac{\rho . V_m^{\ 2}}{2} \tag{4.48}$$

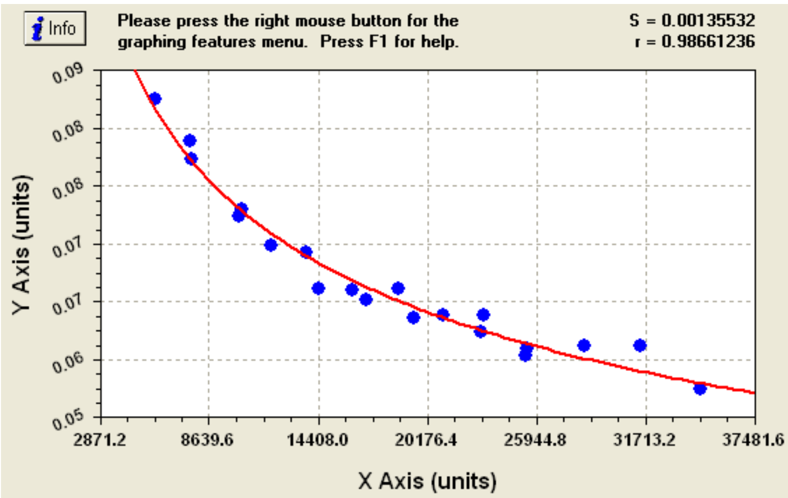

Figure 4.8 Experimental data and curve fitting for Correlation 5

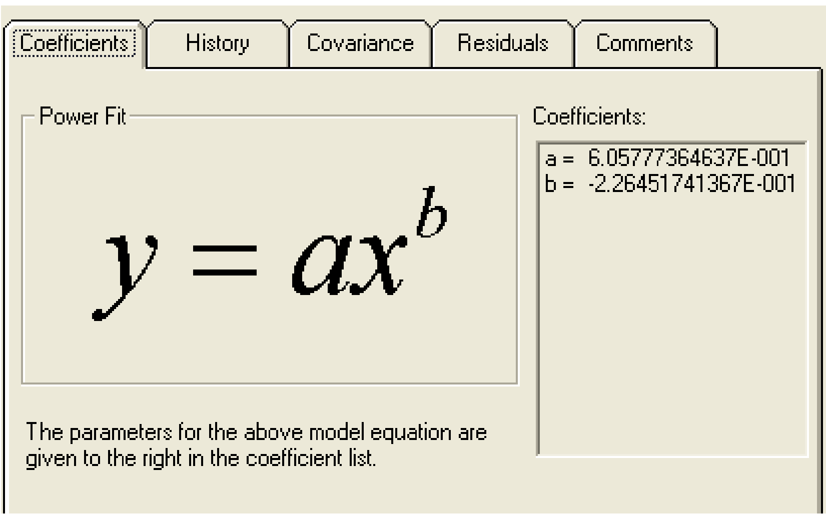

Figure.4.9 Power model information for Correlation 5

4.3 Proportional Error Calculation

Error for experiment is calculated by means of equation below as follows:

$$Error = \frac{1}{N}\sum_{i=!}^{N} \left| \left(\frac{\Pr edictedvalue - Measuredvalue}{Measuredvalue} \right) * 100 \right| \qquad (4.49)$$

CHAPTER 5

RESULTS AND DISCUSSION

In the study, experiments are conducted in order to determine single phase pressure drop characteristic of smooth and microfin tubes and details of experiments are given Table 5.1 as follows:

Table 5.1 Details of operating conditions

Experiment	Inside diameter (m)	Mass flow rate range (kg/s)	Reynolds number range	Hot water inlet temperature (^{o}C)	Cold water inlet temperature (^{o}C)
Smooth Tube 1	0.006	0.023-0.100	7175-31775	40-60	15
Smooth Tube 2	0.008	0.023-0.100	5446-23831	40	15
Simulated Smooth Tube 3	0.00748	0.023-0.100	5825-25488	40	15
Microfin Tube	0.00748	0.023-0.100	5725-25353	40-60	15

5.1 Results for Smooth Tube 1

5.1.1 Pressure Drop Results for Smooth Tube 1

In the experiments effect of the mass flow rate of water on pressure drop is investigated. In order to determine pressure drop 10 experiments were conducted and new correlations are developed. Experimental results compared with Petukhov and Blasius Equations and developed correlations. The results are given in the Table 5.2.

Table 5.2 Pressure drop data and proportional errors of smooth tube 1

			Pressure Drop Results				
Mass flow rate	**Re**	**Mass flux**	**Petukhov**	**Blasius**	**Experiment**	**Correlation 1**	**Correlation 2**
kg/s	-	kg/m^2s	mbar	mbar	mbar	mbar	mbar
0.0233	7175	826	21.763	21.58	24.30	24.14	24.68
0.0312	9700	1103	35.609	35.71	41.10	41.29	41.25
0.0408	12709	1445	56.727	57.30	67.50	67.54	66.78
0.0475	14852	1681	73.626	74.58	86.50	88.45	87.37
0.0575	17989	2035	102.600	104.17	122.00	123.89	122.81
0.0675	21108	2389	135.712	137.93	163.00	163.88	163.47
0.0742	23289	2624	159.846	162.49	191.00	192.78	193.21
0.0833	26187	2949	195.997	199.22	238.00	235.98	237.79
0.0917	28861	3244	231.562	235.26	280.00	278.65	281.72
0.1008	31775	3568	273.725	277.90	339.00	329.92	333.84
Proportional Errors			%	%	%	%	%
			14.84	15.78	-	1.05	0.84

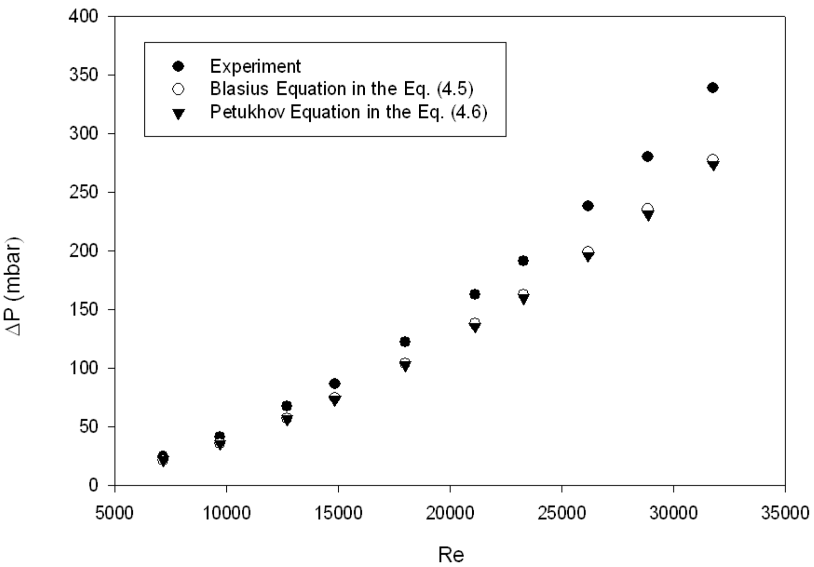

Figure 5.1 Predicted and measured pressure drop results for smooth tube 1 according to Reynolds number

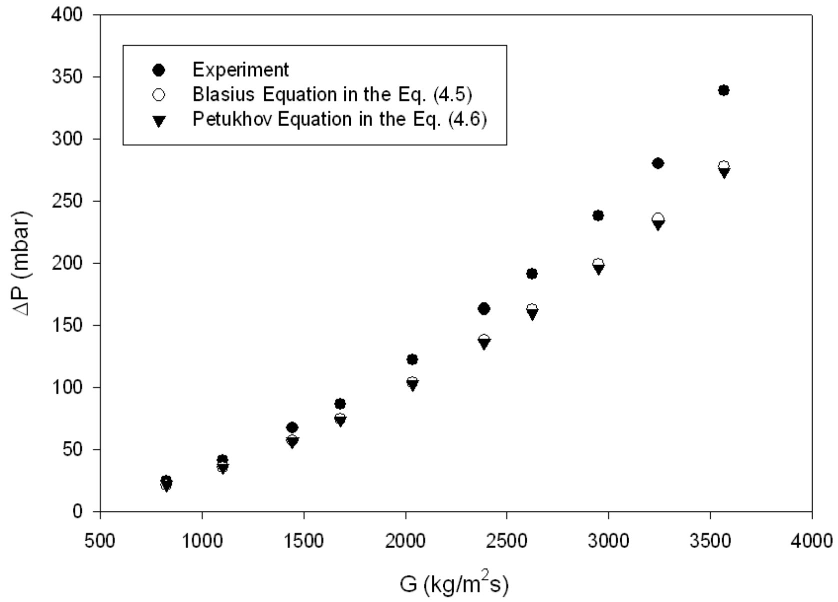

Figure 5.2 Predicted and measured pressure drop results for smooth tube 1 according to mass flux

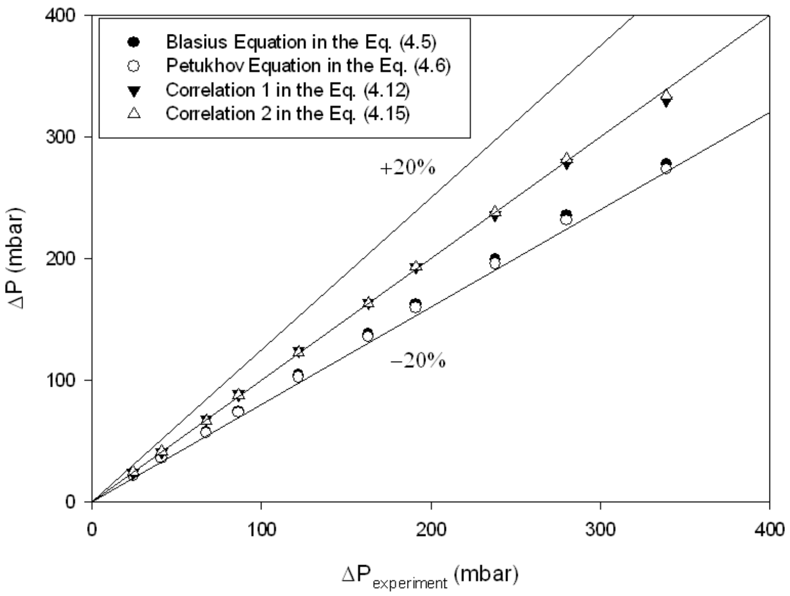

Figure 5.3 Comparison of pressure drop results for the smooth tube 1

5.1.2 Friction Factor Results for Smooth Tube 1

Table 5.3 Friction factor data and proportional errors of smooth tube 1

			Friction Factor Results				
Mass flow rate	**Re**	**Mass flux**	**Petukhov**	**Blasius**	**Experiment**	**Correlation 1**	**Correlation 2**
kg/s	-	kg/m^2s	-	-	-	-	-
0,0233	7175	826	0,0346	0,0343	0,0387	0,0384	0,0393
0,0312	9700	1103	0,0317	0,0318	0,0366	0,0368	0,0368
0,0408	12709	1445	0,0295	0,0298	0,0351	0,0351	0,0347
0,0475	14852	1681	0,0283	0,0286	0,0332	0,0339	0,0335
0,0575	17989	2035	0,0269	0,0273	0,0320	0,0325	0,0322
0,0675	21108	2389	0,0258	0,0262	0,0310	0,0311	0,0311
0,0742	23289	2624	0,0252	0,0256	0,0301	0,0303	0,0304
0,0833	26187	2949	0,0244	0,0248	0,0297	0,0294	0,0297
0,0917	28861	3244	0,0239	0,0242	0,0289	0,0287	0,0290
0,1008	31775	3568	0,0233	0,0237	0,0289	0,0281	0,0284
Proportional Errors			%	%	%	%	%
			14.84	15.78	-	1.05	0.84

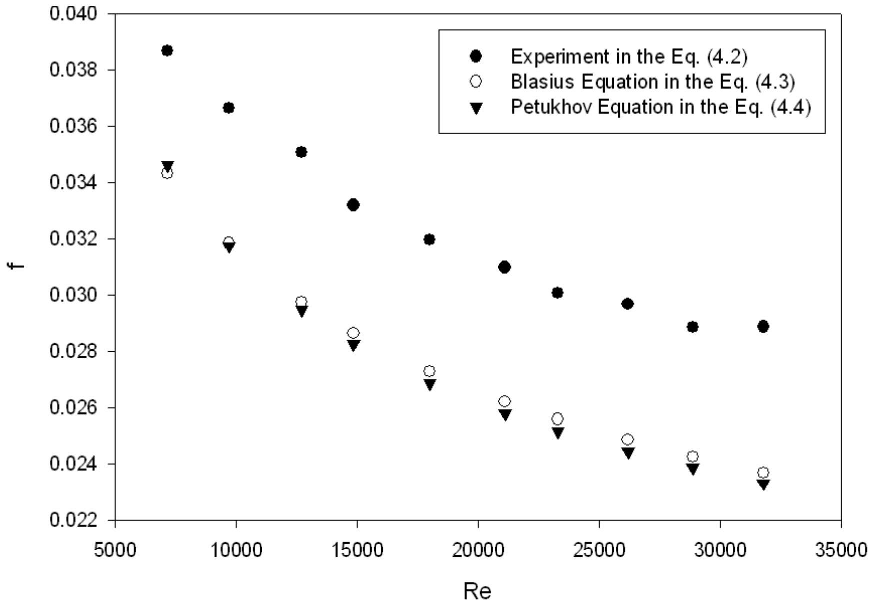

Figure 5.4 Friction factor results for smooth tube 1 according to Reynolds number

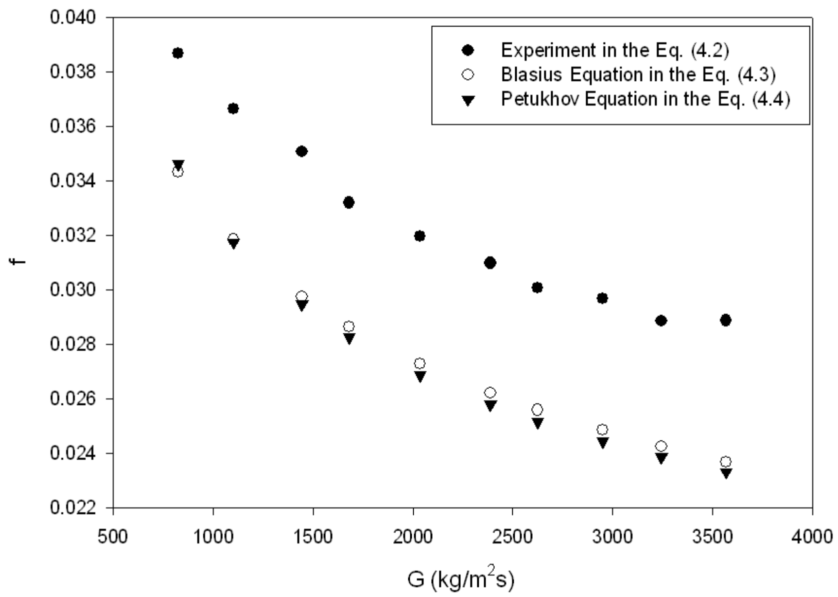

Figure 5.5 Friction factor results for smooth tube 1 according to mass flux

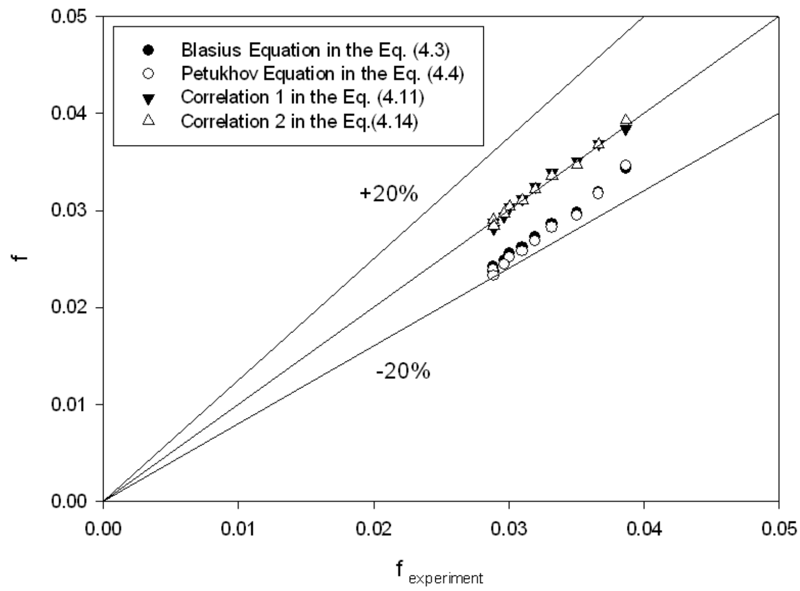

Figure 5.6 Comparison of friction factors results for the smooth tube 1

5.1.3 Wall Shear Stress Results for Smooth Tube 1

Table 5.4 Wall shear stress data of smooth tube 1

			Wall Shear Stress Results				
Mass flow rate	Re	Mass flux	Petukhov	Blasius	Experiment	Correlation 1	Correlation 2
kg/s	-	kg/m^2s	N/m^2	N/m^2	N/m^2	N/m^2	N/m^2
0.0233	7175	826	2.97	2.94	3.31	3.29	3.37
0.0312	9700	1103	4.86	4.87	5.60	5.63	5.63
0.0408	12709	1445	7.74	7.81	9.20	9.21	9.11
0.0475	14852	1681	10.04	10.17	11.80	12.06	11.91
0.0575	17989	2035	13.99	14.21	16.64	16.89	16.75
0.0675	21108	2389	18.51	18.81	22.23	22.35	22.29
0.0742	23289	2624	21.80	22.16	26.05	26.29	26.35
0.0833	26187	2949	26.73	27.17	32.45	32.18	32.43
0.0917	28861	3244	31.58	32.08	38.18	38.00	38.42
0.1008	31775	3568	37.33	37.90	46.23	44.99	45.52

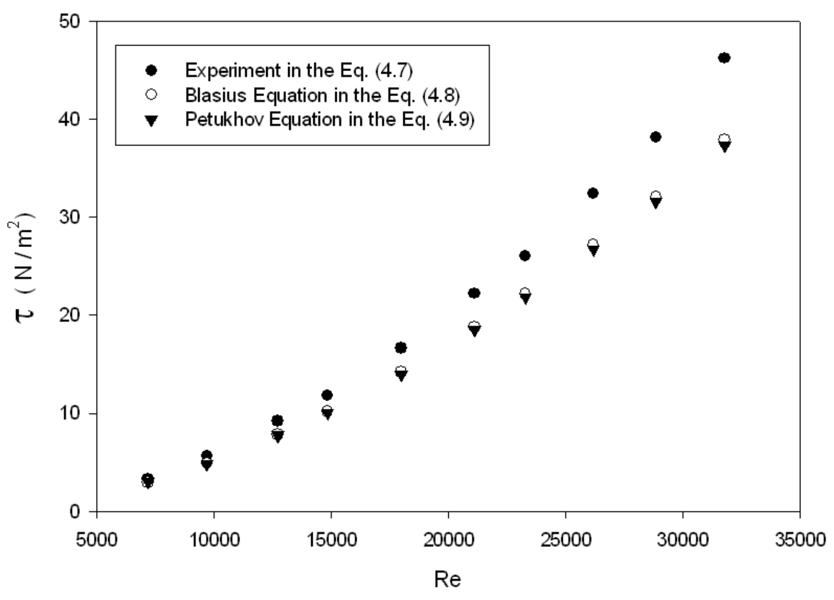

Figure 5.7Surface shear stress results for smooth tube 1 according to Reynolds number

5.2 Results for Smooth Tube 2

5.2.1 Pressure Drop Results for Smooth Tube 2

Table 5.5 Pressure drop data and proportional errors of smooth tube 2

			Pressure Drop Results			
Mass flow rate	**Re**	**Mass flux**	**Petukhov**	**Blasius**	**Experiment**	**Correlation 3**
kg/s	-	kg/m^2s	mbar	mbar	mbar	mbar
0.0233	5446	464	5.611	5.49	8.70	8.18
0.0312	7274	620	9.179	9.11	12.60	12.79
0.0408	9532	812	14.577	14.61	19.00	19.40
0.0475	11139	945	18.887	19.02	23.50	24.46
0.0575	13296	1127	25.613	25.89	31.70	32.10
0.0675	15636	1326	33.951	34.42	40.50	41.26
0.0742	17467	1475	40.823	41.44	49.00	48.55
0.0833	19640	1658	50.001	50.80	60.70	58.10
0.0917	21646	1824	59.022	59.99	70.00	67.24
0.1008	23831	2006	69.710	70.87	81.50	77.86
			%	%	%	%
Proportional Errors			20.54	19.92	-	3.04

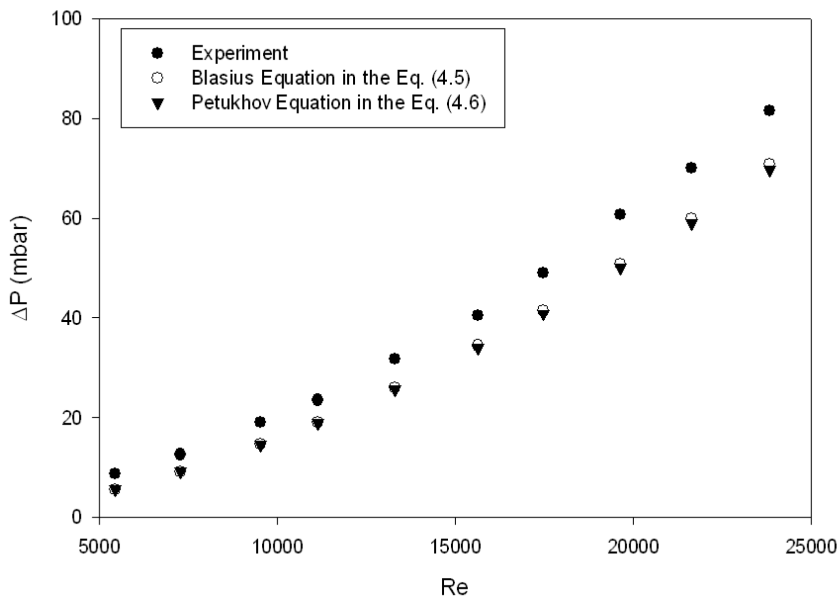

Figure 5.8 Predicted and measured friction factor results for smooth tube2 according to Reynolds number

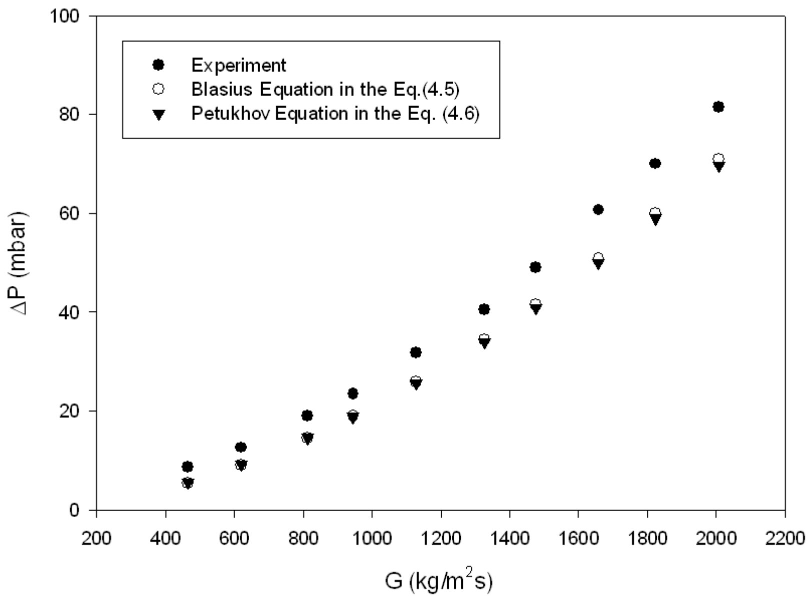

Figure 5.9 Predicted and measured friction factor results for smooth tube 2 according to mass flux

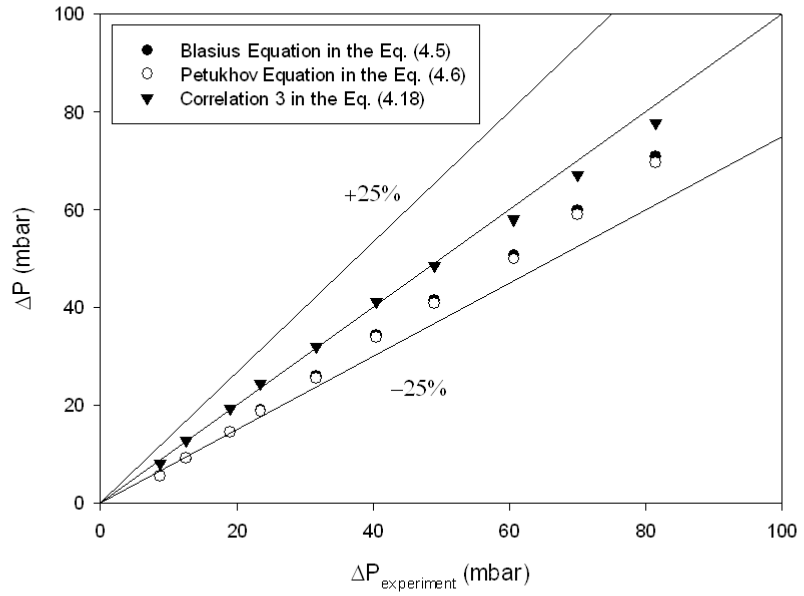

Figure 5.10 Comparison of pressure drop results for the smooth tube 2

5.2.2 Friction Factor Results for Smooth Tube 2

Table 5.6Friction factor data and proportional errors of smooth tube 2

			Friction Factor Results			
Mass flow rate	**Re**	**Mass flux**	**Petukhov**	**Blasius**	**Experiment**	**Correlation 3**
kg/s	-	kg/m2s	-	-	-	
0.0233	5446	464	0.0376	0.0368	0.0583	0.0549
0.0312	7274	620	0.0345	0.0342	0.0473	0.0481
0.0408	9532	812	0.0319	0.0320	0.0416	0.0425
0.0475	11139	945	0.0305	0.0308	0.0380	0.0396
0.0575	13296	1127	0.0291	0.0294	0.0360	0.0365
0.0675	15636	1326	0.0279	0.0283	0.0333	0.0339
0.0742	17467	1475	0.0271	0.0275	0.0325	0.0322
0.0833	19640	1658	0.0263	0.0267	0.0319	0.0305
0.0917	21646	1824	0.0256	0.0261	0.0304	0.0292
0.1008	23831	2006	0.0250	0.0254	0.0292	0.0279
Proportional Errors			%	%	%	%
			20.54	19.92	-	3.04

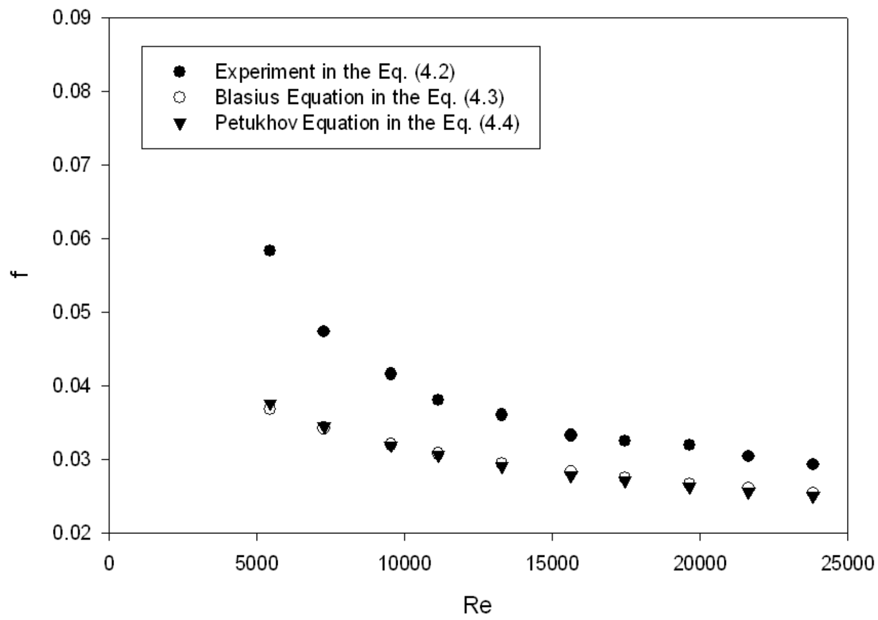

Figure 5.11Friction factor results for smooth tube 2 according to Reynolds number

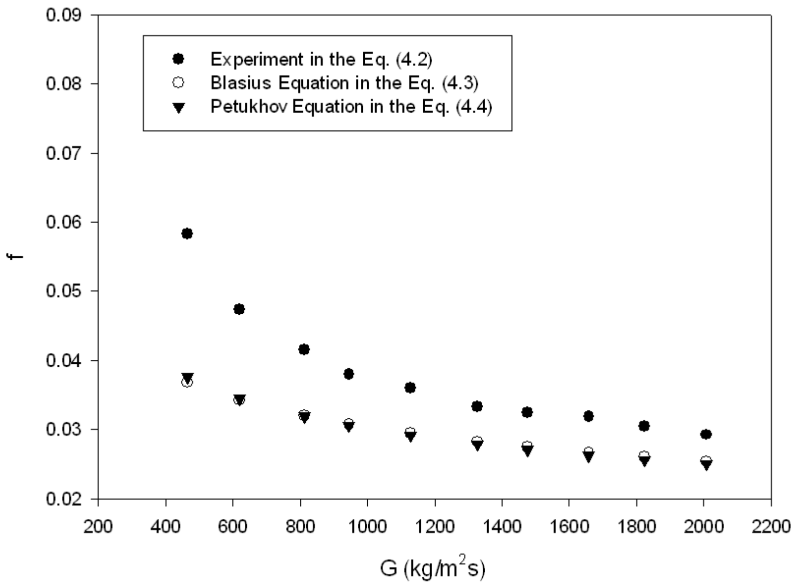

Figure 5.12Friction factor results for smooth tube2 according to mass flux

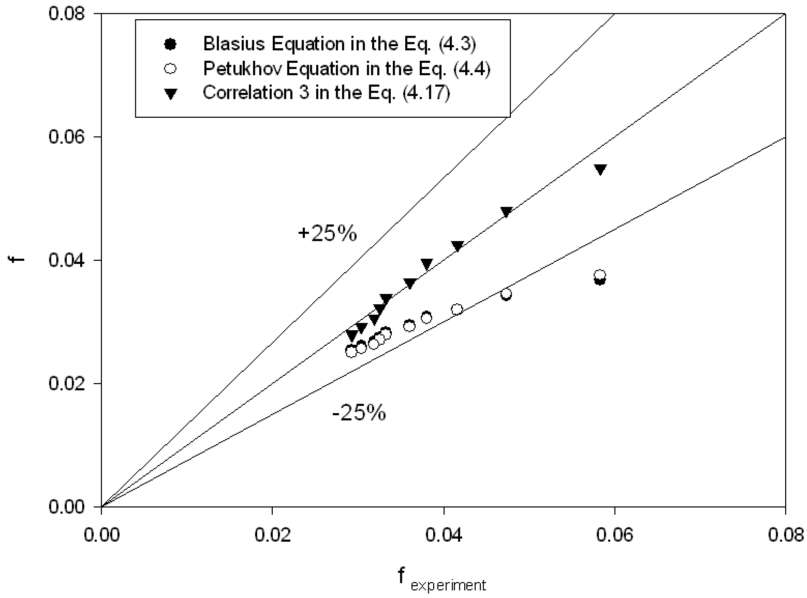

Figure 5.13 Comparison of friction factor results for the smooth tube 2

5.2.3 Wall Shear Stress Results for Smooth Tube 2

Table 5.7Wall shear stress data and proportional errors of smooth tube 2

			Wall Shear Stress Results			
Mass flow rate	Re	Mass flux	Petukhov	Blasius	Experiment	Correlation 3
kg/s		kg/m2s	(N/m2)	(N/m2)	(N/m2)	
0.0233	5446	464	1.02	1.00	1.58	1.49
0.0312	7274	620	1.67	1.66	2.29	2.33
0.0408	9532	812	2.65	2.66	3.45	3.53
0.0475	11139	945	3.43	3.46	4.27	4.45
0.0575	13296	1127	4.66	4.71	5.76	5.84
0.0675	15636	1326	6.17	6.26	7.36	7.50
0.0742	17467	1475	7.42	7.53	8.91	8.83
0.0833	19640	1658	9.09	9.24	11.04	10.56
0.0917	21646	1824	10.73	10.91	12.73	12.23
0.1008	23831	2006	12.67	12.88	14.82	14.16

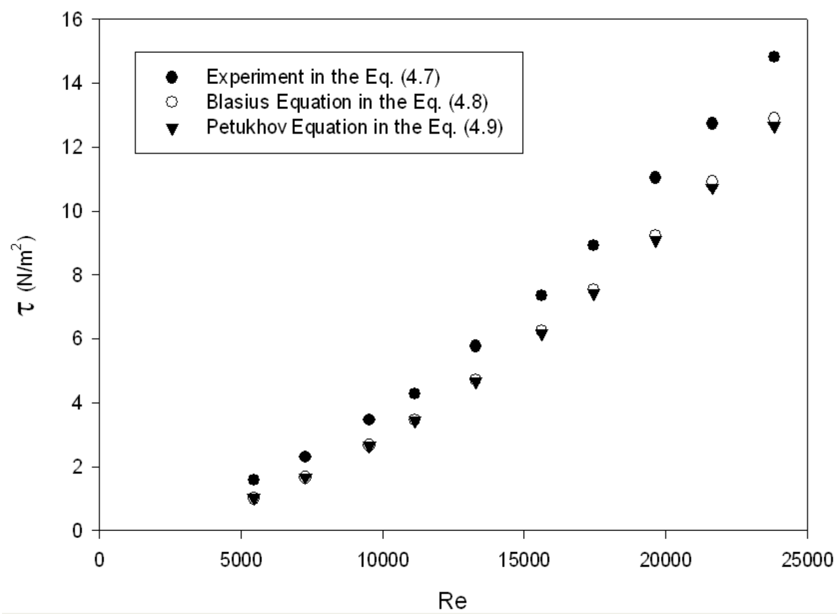

Figure 5.14 Surface shear stress results for smooth tube 2 according to Reynolds number

5.3 Results for Simulated Smooth Tube 3

5.3.1 Pressure Drop Results for Simulated Smooth Tube 3

Table 5.8Pressure drop data and proportional errors of smooth tube 3

			Pressure Drop Results		
Mass flow rate	**Re**	**Mass flux**	**Petukhov**	**Blasius**	**Experiment (Correlation 4)**
kg/s	-	kg/m^2s	mbar	mbar	Mbar
0.0233	5825	531	7.693	7.55	8.70
0.0312	7780	709	12.595	12.53	13.60
0.0408	10195	929	20.017	20.11	21.47
0.0475	11913	1081	25.947	26.17	28.02
0.0575	14220	1290	35.202	35.63	38.54
0.0675	16723	1517	46.680	47.36	52.01
0.0742	18681	1688	56.142	57.02	63.42
0.0833	21005	1896	68.782	69.91	78.97
0.0917	23150	2086	81.209	82.55	94.58
0.1008	25488	2295	95.934	97.52	113.41
			%	%	%
Proportional Errors			10.59	9.88	-

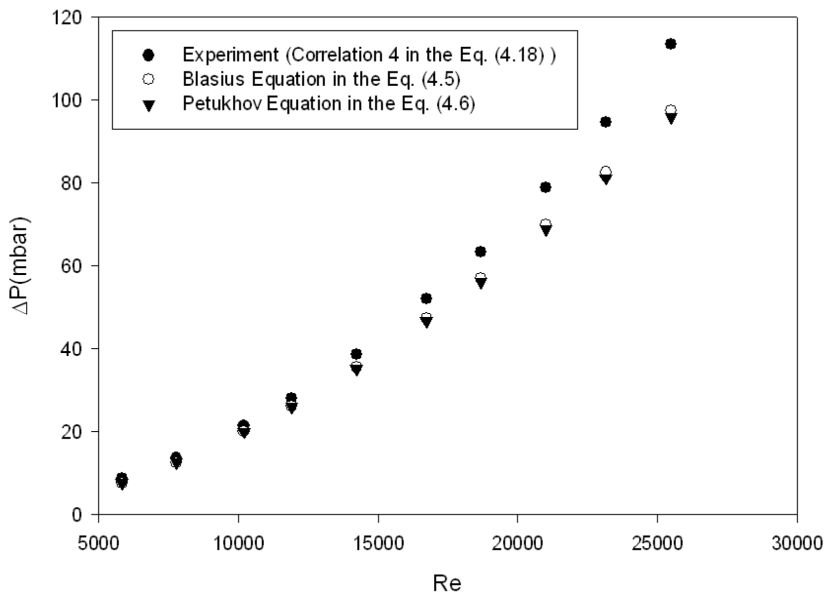

Figure 5.15 Predicted and measured pressure drop results for smooth tube 3 according to Reynolds number

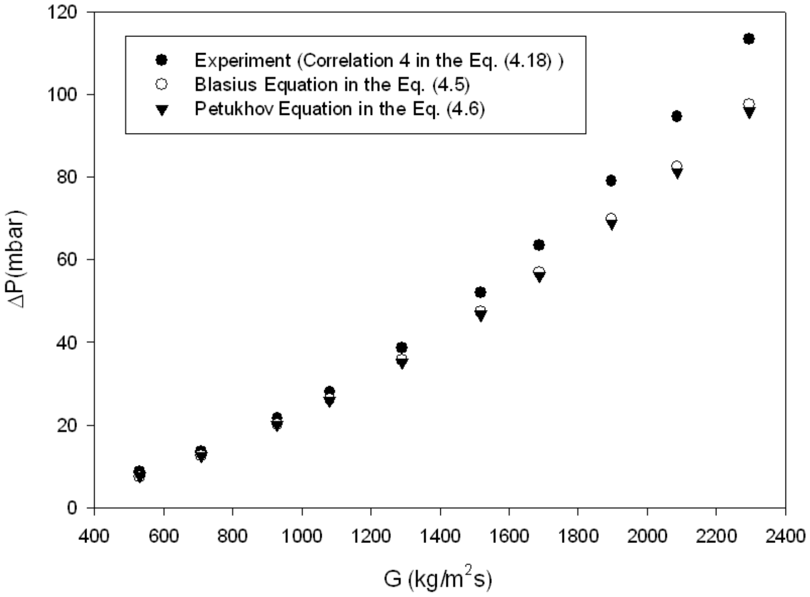

Figure 5.16 Predicted and measured pressure drop results for smooth tube 3 according to mass flux

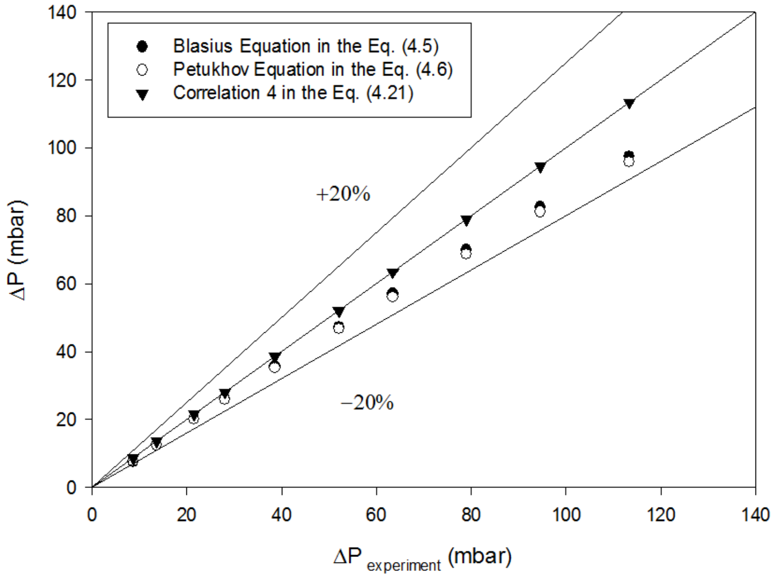

Figure 5.17 Comparison of pressure drop results for the smooth tube 3

5.3.2 Friction Factor Results for Simulated Smooth Tube 3

Table 5.9Friction factor data and proportional errors of smooth tube 3

Mass flow rate	Re	Mass flux	Friction Factor Results Petukhov	Blasius	Experiment (Correlation 4)
kg/s	-	kg/m2s	-	-	-
0.0233	5825	531	0.0369	0.0362	0.0417
0.0312	7780	709	0.0338	0.0336	0.0365
0.0408	10195	929	0.0313	0.0314	0.0336
0.0475	11913	1081	0.0300	0.0302	0.0324
0.0575	14220	1290	0.0286	0.0289	0.0313
0.0675	16723	1517	0.0274	0.0278	0.0305
0.0742	18681	1688	0.0266	0.0270	0.0301
0.0833	21005	1896	0.0258	0.0262	0.0297
0.0917	23150	2086	0.0252	0.0256	0.0294
0.1008	25488	2295	0.0246	0.0250	0.0291
			%	%	%
Proportional Errors			10.59	9.88	-

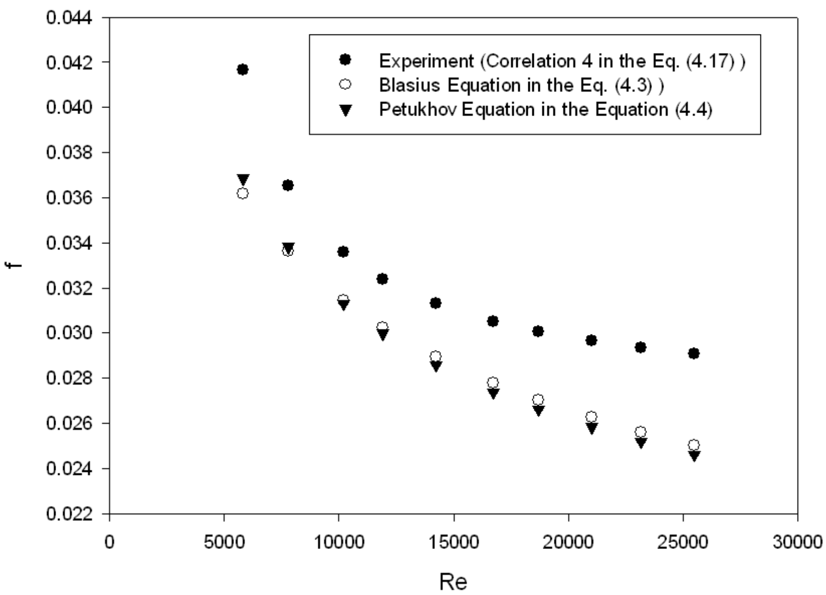

Figure 5.18Friction factor results for smooth tube 3 according to Reynolds number

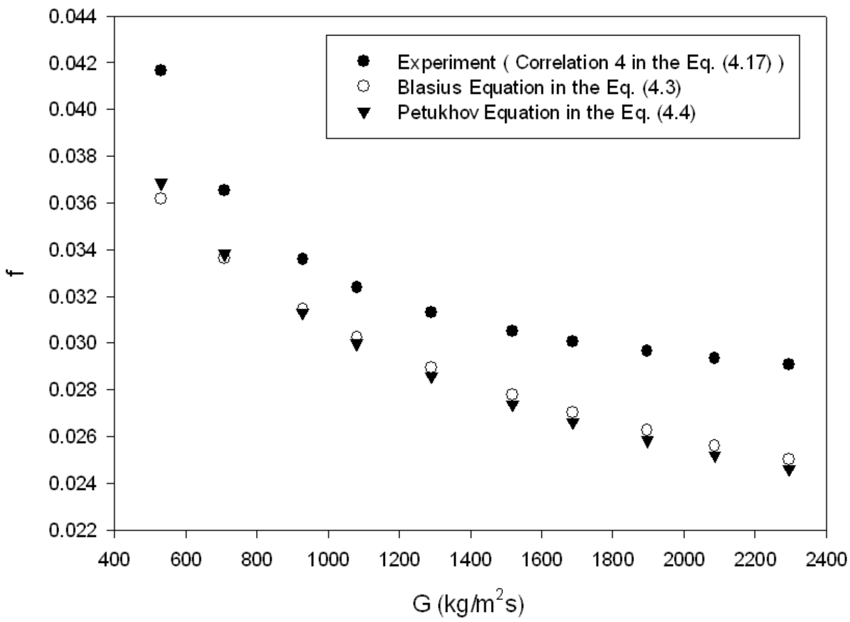

Figure 5.19Friction factor results for smooth tube according to mass flux

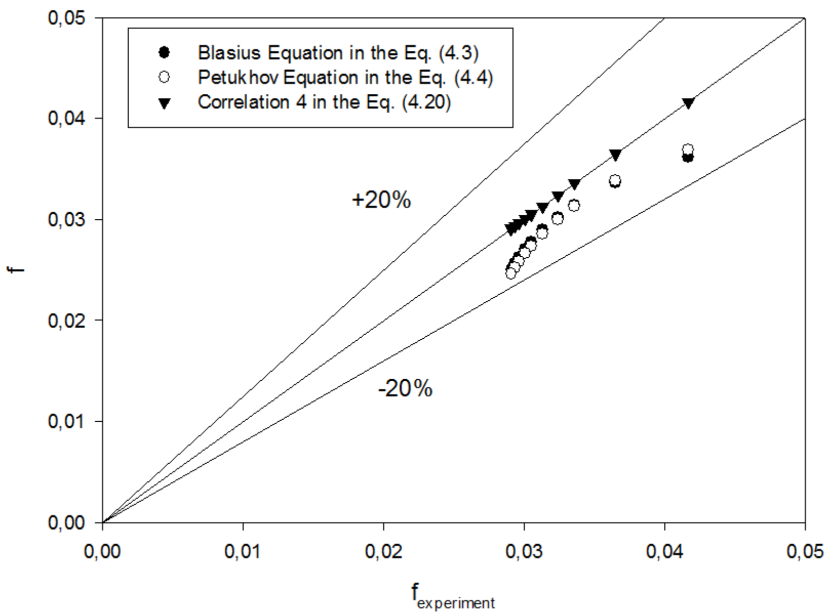

Figure 5.20 Comparison of friction factor results for the smooth tube 3

5.3.3 Wall Shear Stress Results for Simulated Smooth Tube 3

Table 5.10Wall shear stress data and proportional errors of smooth tube 3

			Wall Shear Stress Results		
Mass flow rate	**Re**	**Mass flux**	**Petukhov**	**Blasius**	**Experiment (Correlation 4)**
kg/s		kg/m^2s	(N/m^2)	(N/m^2)	(N/m^2)
0.0233	5825	531	1.31	1.28	1.48
0.0312	7780	709	2.14	2.13	2.31
0.0408	10195	929	3.40	3.42	3.65
0.0475	11913	1081	4.41	4.45	4.76
0.0575	14220	1290	5.98	6.06	6.55
0.0675	16723	1517	7.94	8.05	8.84
0.0742	18681	1688	9.54	9.69	10.78
0.0833	21005	1896	11.69	11.88	13.42
0.0917	23150	2086	13.81	14.03	16.08
0.1008	25488	2295	16.31	16.58	19.28

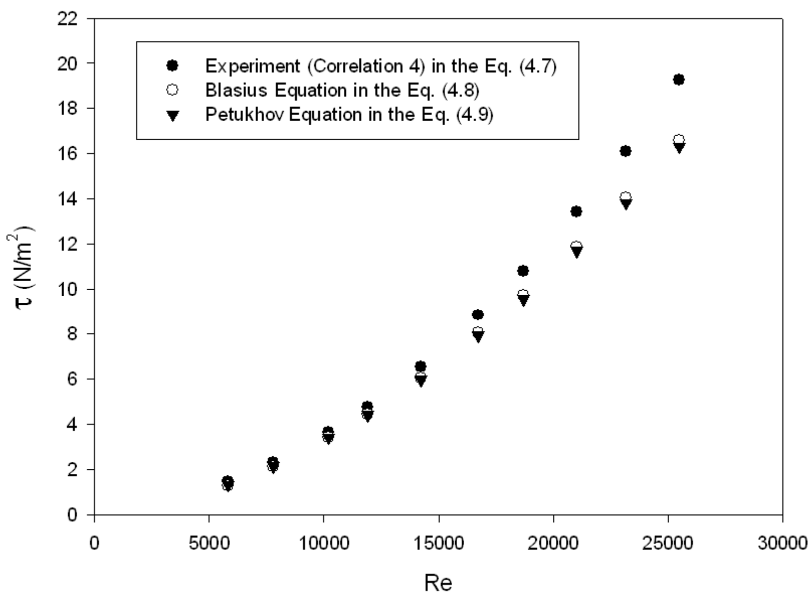

Figure 5.21Surface shear stress results for smooth tube 3 according to Reynolds number

5.4. Results for Microfin Tube

5.4.1 Pressure Drop Results for Microfin Tube

Table5.11 Pressure drop data and proportional errors of microfin tube

			Pressure Drop Results									
Mass flow rate	**Re**	**Mass flux**	**Siddique**	**Al Fahed**	**Jensen**	**Haaland**	**Wang**	**Zdaniuk**	**Webb**	**Exp.**	**Correlation 5**
kg/s	-	kg/m2s	mbar	mbar	mbar	mbar	mbar	mbar	mbar	mbar	mbar
0.0233	5725	526	15.52	15.89	17.31	12.60	10.22	6.59	4.77	18.00	17.35
0.0312	7657	695	24.94	25.47	28.11	21.56	17.77	10.53	7.68	29.20	28.37
0.0408	10140	920	40.37	41.13	45.95	37.23	31.05	16.95	12.44	47.40	46.69
0.0475	11850	1070	52.25	53.17	59.81	50.03	41.93	21.88	16.11	61.50	61.00
0.0575	14353	1295	72.48	73.64	83.54	72.77	61.30	30.24	22.36	84.40	85.59
0.0675	16842	1521	95.21	96.82	110.62	99.75	84.29	39.69	29.45	114.40	113.76
0.0742	18582	1671	112.01	113.57	130.32	120.09	101.65	46.50	34.58	140.60	134.33
0.0833	20894	1877	136.74	138.51	159.77	151.15	128.14	56.65	42.24	170.00	165.14
0.0917	23027	2065	160.92	162.87	188.68	182.46	154.85	66.54	49.72	205.70	195.47
0.1008	25353	2271	189.43	191.57	222.88	220.32	187.14	78.97	58.54	235.70	231.43
Proportional Errors			%	%	%	%	%	%	%	%	%
			17.0	15.7	4.7	16.6	30.0	65.3	74.4	-	2.5

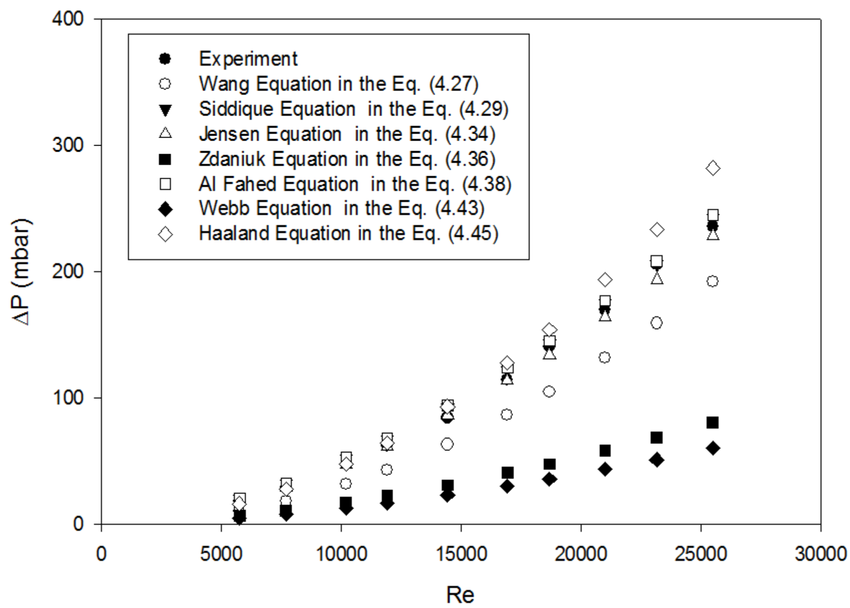

Figure 5.22 Predicted and measured pressure drop results for microfin tube according to Reynolds number

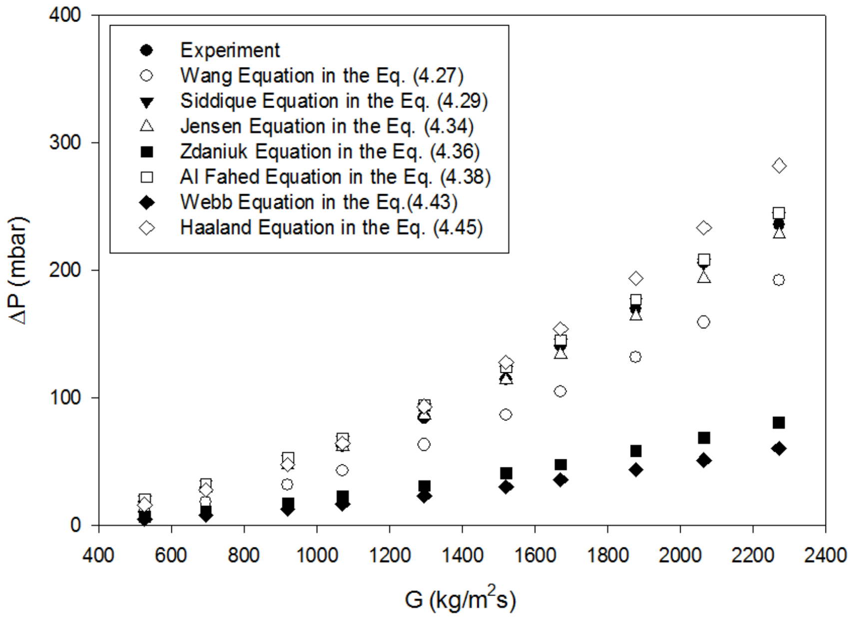

Figure 5.23 Predicted and measured pressure drop results for microfin tube according to mass flux

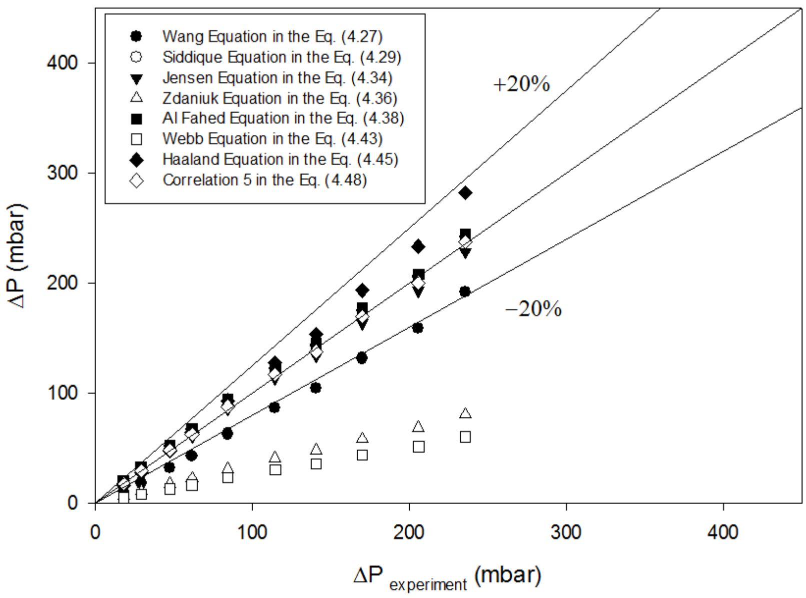

Figure 5.24 Comparison of pressure drop results for the microfin tube

5.4.2 Friction Factor Results for Microfin Tube

Table 5.12Friction factor data and proportional errors of microfin tube

			Friction Factor Results								
Mass flow rate	**Re**	**Mass flux**	**Siddique**	**Al Fahed**	**Jensen**	**Haaland**	**Wang**	**Zdaniuk**	**Webb**	**Experiment**	**Correlation 5**
kg/s	-	kg/m^2s	-	-	-	-	-	-	-	-	-
0.0233	5725	526	0.076	0.078	0.085	0.062	0.050	0.032	0.023	0.086	0.085
0.0312	7657	695	0.070	0.071	0.079	0.060	0.050	0.029	0.021	0.080	0.079
0.0408	10140	920	0.064	0.066	0.073	0.059	0.049	0.027	0.020	0.074	0.074
0.0475	11850	1070	0.061	0.063	0.070	0.059	0.049	0.026	0.019	0.071	0.072
0.0575	14353	1295	0.058	0.059	0.067	0.058	0.049	0.024	0.018	0.066	0.069
0.0675	16842	1521	0.056	0.056	0.064	0.058	0.049	0.023	0.017	0.065	0.066
0.0742	18582	1671	0.0544	0.0552	0.0633	0.0585	0.0495	0.0226	0.0169	0.0666	0.0653
0.0833	20894	1877	0.0527	0.0533	0.0615	0.0583	0.0494	0.0218	0.0163	0.0638	0.0636
0.0917	23027	2065	0.0512	0.0518	0.0600	0.0581	0.0493	0.0212	0.0159	0.0638	0.0622
0.1008	25353	2271	0.0498	0.0504	0.0586	0.0580	0.0493	0.0206	0.0155	0.0604	0.0609
Proportional Errors			%	%	%	%	%	%	%	%	%
			17.0	15.7	2,36	16.6	30.0	65.3	74.4	-	2,5

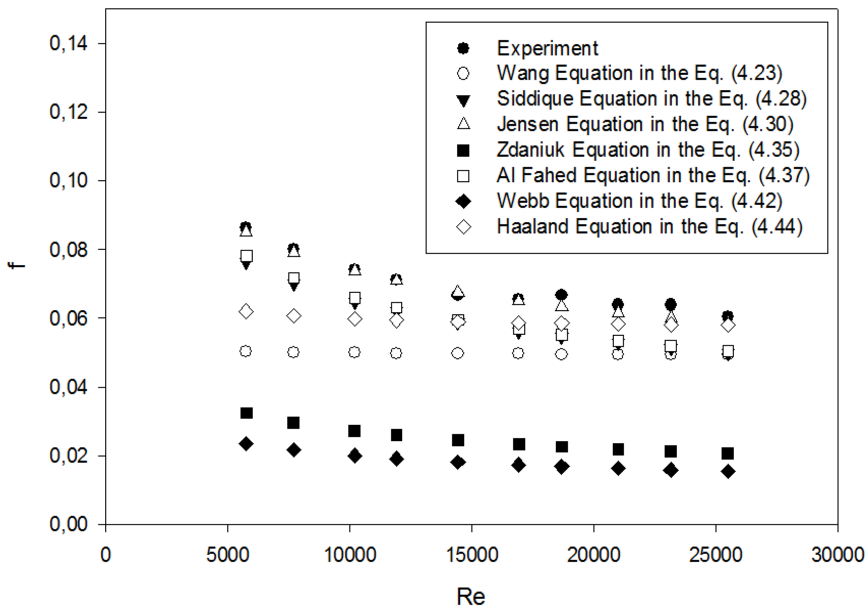

Figure 5.25Friction factor results for smooth tube according to Reynolds number for the microfin tube

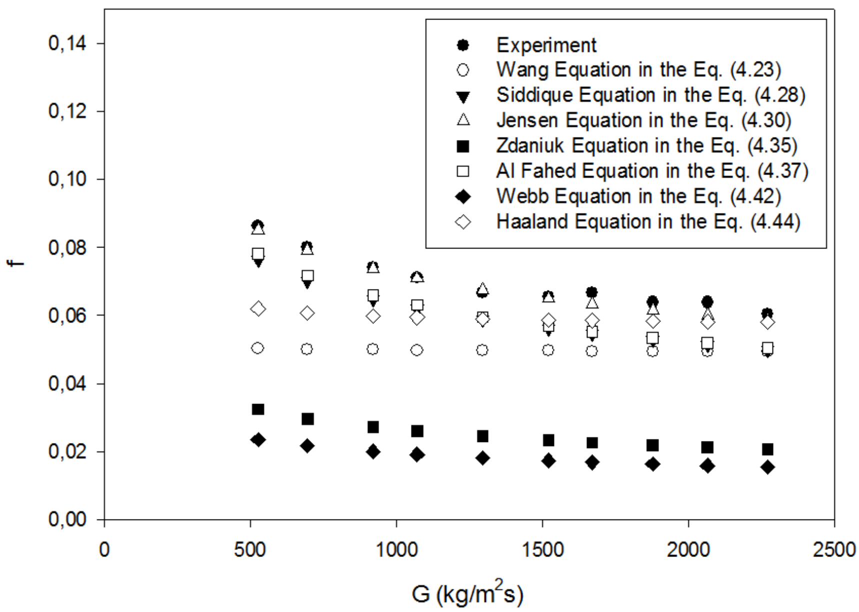

Figure 5.26Friction factor results for smooth tube according to mass flux for the microfin tube

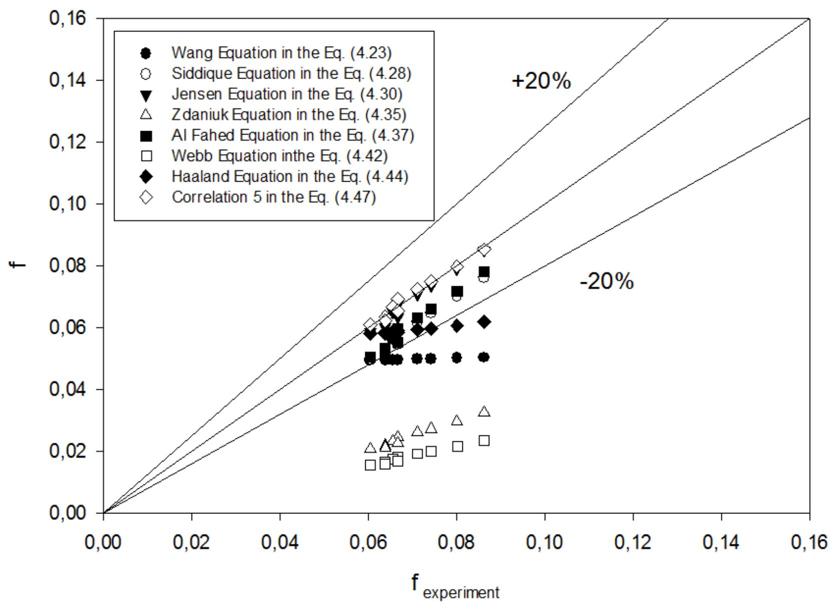

Figure 5.27Comparison of friction factor results for the microfin tube

5.5 Pressure Drop Comparison of Smooth Tubes Having Different Inside Diameter

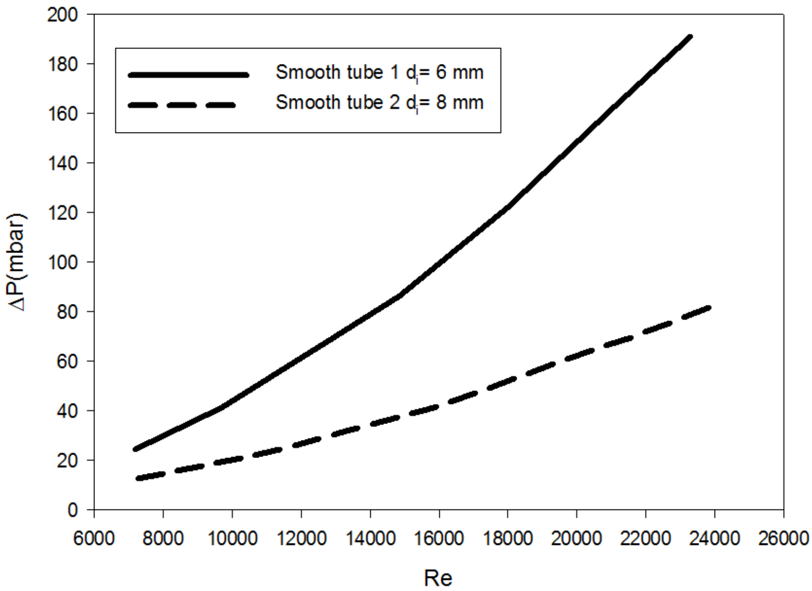

Figure 5.28 Pressure drop comparison of smooth tubes according to Reynolds number

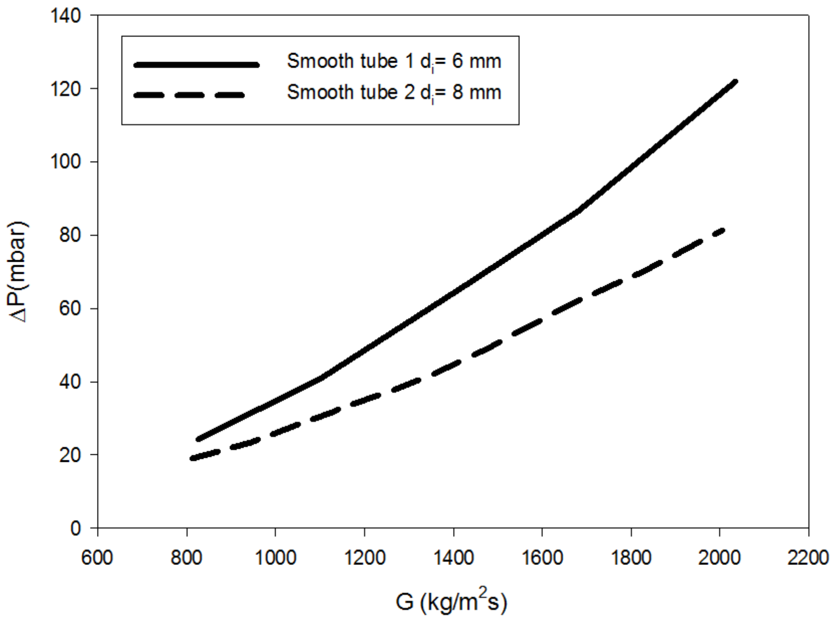

Figure 5.29 Pressure drop comparison of smooth tubes according to mass flux

5.6 Pressure Drop Comparison of Smooth and Microfin Tubes

Table 5.13 Experimental pressure drop data for smooth and microfin tubes

Smooth Tube			Microfin Tube			Pressure Drop Augmentation
Re	G	ΔP	Re	G	ΔP	
-	kg/m2s	mbar	-	kg/m2s	mbar	$P_{microfin}/P_{smooth}$
5809	528	8.70	5725	526	18.00	2.07
7759	705	13.60	7657	695	29.20	2.15
10167	924	21.47	10140	920	47.40	2.21
11881	1075	28.02	11850	1070	61.50	2.19
14183	1283	38.54	14353	1295	84.40	2.19
16678	1509	52.01	16842	1521	114.40	2.20
18631	1679	63.42	18582	1671	140.60	2.22
20949	1886	78.97	20894	1877	170.00	2.15
23089	2075	94.58	23027	2065	205.70	2.17
25420	2282	113.41	25353	2271	235.70	2.08

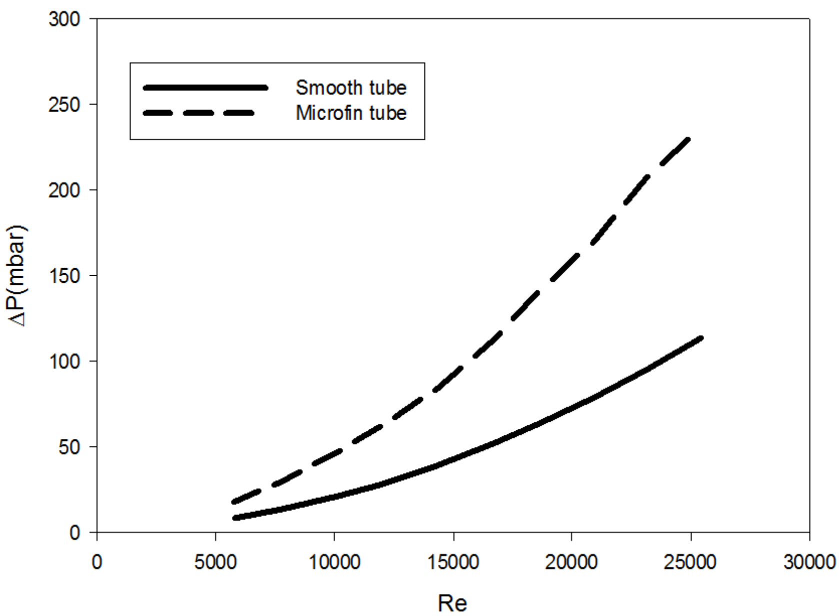

Figure 5.30 Pressure drop comparison of smooth and microfin tubes according to Reynolds number

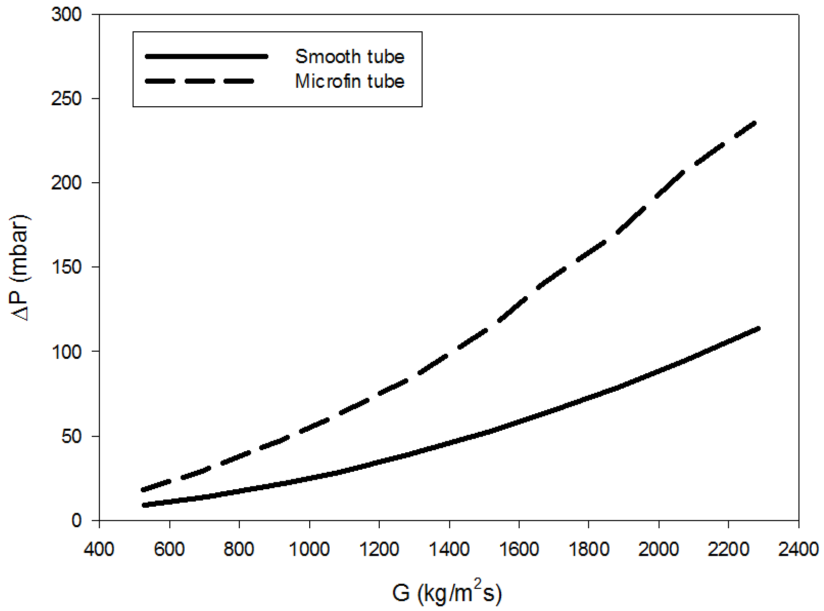

Figure 5.31Pressure drop comparison of smooth and microfin tubes according to mass flux

CHAPTER 6

CONCLUSIONS AND SUGGESTIONS

- It was found that the friction factor decreased gradually as the Reynolds number increased for both smooth and microfin tube. With increase in Reynolds number, the thickness of sublayer decreases and hence in tube turbulent flow becomes more uniform.

- It was found that the pressure drop increased gradually as the Reynolds number increased for both smooth and microfin tube.

- The pressure drop in smooth tube having lower inside diameter was higher than in the smooth tube having higher inside diameter.

- The friction factor and pressure drop parameters for the microfin tube were higher than those for the smooth tube. This implies that the microfin tubes produced more flow disturbance by the occurrence of the swirl flow and flow recirculation produced by the fins, which led to higher frictional pressure drop.

- Experimental results for smooth tubes compared with equations given in the literature. It is shown that there was good agreement for smooth tube result.

- Experimental results for microfin tube compared with equations given in the literature. It is shown that there was conflict about predict of microfin tube pressure drop characteristic prediction. By the means of experimental data, new correlation was developed in order to predict friction factor for microfin tube.

- New tubes having different geometrical parameters can be used experiments in order to predict pressure drop characteristic of microfin tubes.

6.1 Future Works

- New tubes having different geometrical parameters will be used in experiments in order to predict pressure drop characteristic of smooth and microfin tubes.
- Convective heat transfer coefficient of various smooth and microfin tubes will be investigated after some alterations on the experimental setup have been performed.
- Tube orientation (horizontal flow, upward flow, downward flow) on the characteristics of in tube single-phase flow will be investigated in the near future.
- Different working fluids such as alternative refrigerants will be used in the experiments after the completion of pressure leakages.
- The number of measured data will be increased for the artificial intelligence techniques (artificial neural network (ANN), fuzzy logic (FL), Adaptive Network based Fuzzy Inference System (ANFIS) and Data Mining (DM))
- Simulation of nanofluid flow in the tested tubes will be performed by means of CFD programs.
- International journal and conference papers will be prepared considering the results of the study and the papers, which have already been published by the author, given below:
  - A.S. Dalkilic A. Celen, M. Awad, S. Wongwises, A critical review on the determination of convective heat transfer coefficient during condensation in smooth and enhanced tubes, abstract accepted by ASME 2013 Summer Heat Transfer Conference, USA
  - A.S. Dalkilic A. Celen, M. Awad, S. Wongwises, A critical review on the determination of convective pressure drop during condensation in smooth and

enhanced tubes, abstract accepted by ASME 2013 Summer Heat Transfer Conference, USA.

- M. Balcilar, A.S. Dalkilic, A. Celen, A.C. Sonmez, S. Wongwises, Classification of in-tube boiling R134a data belonging to the smooth and corrugated tubes, submitted to Polish Journal of Chemical Technology, 08.12.2012.
- A.S. Dalkilic, N. Kayacı, M. Tabatabaei, O. Yıldız, A. Celen, W. Daungthongsuk, S. Wongwises, Forced convective heat transfer of nanofluids - A review of the recent literature, Current Nanoscience 8 (2012) 949-969.
- N. Kayaci, M. Balcilar, M. Tabatabaei, A. Celen, O. Yıldız, A.S. Dalkilic, S. Wongwises, Determination of the single-phase forced convection heat transfer characteristics of TiO2 nanofluids flowing in smooth and micro-fin tubes by means of CFD and ANN analyses, Current Nanoscience, "Accepted for Publication-Article in Press".
- NurullahKayaci, Ali Celen, Mehdi Tabatabei, OğuzhanYıldız, AhmetSelimDalkılıç, SomchaiWongwises, Numerical investigation of heat trasfer enhancement using water based nanofluids flowing in enhanced tubes, ASME 2012 International Mechanical Engineering Congress & Exposition (2012) November 9-15, USA.
- M. Balcilar, A. Celen, N. Kayaci, A.S. Dalkilic, S. Wongwises, A critical review on the numerical methods of two-phase flows, ASME 2012 International Mechanical Engineering Congress & Exposition (2012) November 9-15, USA.
- A.S. Dalkilic, N. Kayacı, A. Celen, W. Daungthongsuk, S. Wongwises, Critical Review on the Determination of Physical Properties of Nanofluids for the Convective Heat Transfer in Tubes, The 3rd TSME International Conference on Mechanical Engineering (2012) October 24-26, Thailand.

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