Proceedings of NHTC'01
35th National Heat Transfer Conference
June 10-12, 2001, Anaheim, California

NHTC01- 12134

EFFECT OF CHANNEL ROUGHNESS ON HEAT TRANSFER AND FLUID FLOW CHARACTERISTICS AT LOW REYNOLDS NUMBERS IN SMALL DIAMETER TUBES

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ABSTRACT

The effect of roughness on pressure drop and heat transfer in circular tubes has been extensively studied in literature. The pioneering work of Nikuradse (1933) established the sand grain roughness as a major parameter in defining the friction factor during laminar and turbulent flows. Recent studies have indicated a transition to turbulent flows at Reynolds number values much below 2300 during single-phase flow in channels with small hydraulic diameters. In the present work, a detailed experimental study is undertaken to investigate the roughness effects in small diameter tubes. The roughness of the inside tube surface is changed by etching it with an acid solution. Two tubes of 1.032 mm and 0.62 mm inner diameter are treated with acid solutions to provide three different roughness values for each tube. The Reynolds number range for the tests is 500-2600 for 1.062mm tube and 900-3000 for 0.62mm tube.

NOMENCLATURE

B: Bias %
C_p: Specific heat (kJ/kg K)
D_h: Hydraulic diameter of the tube (mm)
e/d: Relative roughness value
f: friction factor
k_f: Thermal conductivity of the fluid (W/m^2 K)
Nu: Nusselt Number $\left(\frac{h\times D}{k_f}\right)$
n: Sample Population
$\dot{m}$: Mass flow rate (kg/s)
P_{in}: Input Power (W)
Pr: Prandtl Number $\left(\frac{\mu\times C_p}{k_f}\right)$
P: Precision error %
Q: Heat transfer rate (W)
q": Heat flux (W/m^2)
$\dot{q}$:Heat generation rate (W/m^3)
Re: Reynolds Number
Ra: Average roughness value of the surface (μm)
r_1: Inner radius of the tube (mm)
r_2: Outer radius of the tube (mm)
t: 't' value from the student T-table
T_{win}: Inlet Wall temperature of the test section (C)
T_{wmid}: Middle Wall temperature of the test section (C)
T_{wout}: Outlet Wall temperature of the test section (C)
T_w: Wall temperature (C)
T_f: Fluid temperature (C)
U: Uncertainty %
V: Voltage (V)
x: Axial or streamwise coordinate in Cartesian, mm
x*: Dimensionless axial coordinate for the thermal entrance region ($\frac{x}{D\times Pr\times Re}$)
X_h: Hydrodynamic entrance length (mm)
X_{th}: Thermal entrance length (mm)
σ_s: Standard deviation of the sample
μ: Viscosity of the fluid (kg/m^2 s)

INTRODUCTION

Single and two-phase flow and heat transfer in small channels is receiving considerable attention recently in an effort to enhance the performance of heat exchange equipment. It is well known that by decreasing the channel size we get an enhancement in the heat transfer coefficient, while the pressure drop also goes up.

Surface roughness plays an important role in the heat transfer and pressure drop characteristics of fluid flow in a channel. The dimensionless surface roughness has been characterized as an important variable in pipe flow. For small hydraulic diameter passages, the small roughness features on the wall play an important role in heat transfer and pressure drop characteristics of the flow.

The present work focuses on studying the effect of roughness on heat transfer and pressure drop characteristics of 0.62mm and 1.067mm tube inner diameter.

LITERATURE REVIEW

There are very few studies reported in literature concerning the effect of surface roughness on heat and flow characteristics in small channels. Hence a brief overview of what has been done in the past is been presented below.

As early as in nineteenth century, Darcy (1858) conducted careful pressure drop experiments on pipes of different materials and roughness, and established that the flow depended on the pipe roughness, pipe diameter, and slope. Nikuradse's (1933) conducted exhaustive experiments to study the effect of roughness on flow characteristics in circular pipes. Experimental data were obtained for water flowing in pipes of six different relative roughness surfaces with Re ranging from 600 to 10^6. The dimensions of the test pipes were 25,50 and 100mm. Their work established the effect of relative roughness, (ε/D), on the flow characteristics.

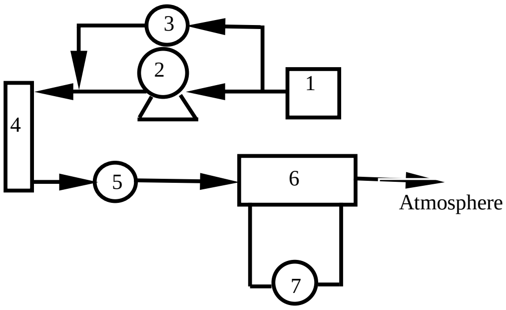
Since the relative roughness, (ε/D), affects the flow characteristics, the same surface roughness value has different effects on large and small diameter tubes. For example, a commercial heat exchanger tube of 10 mm diameter may be considered as a smooth tube, while the same surface finish may result in a rough tube for a 0.2 mm diameter tube.

Some of the other recent work on roughness studies in small channels is summarized in the Table 1 below.

The work available in literature clearly indicates that the roughness affects the laminar to turbulent transition, as well as the flow and heat transfer characteristics. The present work is aimed at studying the effect of surface roughness on pressure drop and heat transfer in 0.62 and 1.067 mm diameter stainless steel tubes.

EXPERIMENTAL SETUP

Experimental loop for conducting test is shown in the Fig. 1. The test facility is an open system with the outlet exposed to atmosphere. Water flows from the tank to the flow meter (0-200 cc/min) into the test section as shown in the Fig. 1. A positive displacement pump (Bronze Gear Pump, 1/3 Hp) is used to pump water from the tank. A relief valve is provided at the outlet of the pump as a protection for high pressures in the system. Flow meter is provided with a control valve to adjust the mass flow rate through the test section. In addition a needle valve (316 SS), not shown, is used before the test section. This helps to reduce oscillations in the flow. Distilled water is used as the working fluid because of the small dimension of the tubes as tap water may cause problems of clogging inside the tube. The pressure transducer is used to measure the pressure drop across the test section. The pressure transducer (Wet/Wet Differential, 0-5 psi) is interfaced with the LabView program to acquire the data.



1. Water tank 2. Water Pump
3. By pass valve 4. Flow Meter
5. Bypass Valve 6. Test Section
7. Pressure transducer

Figure 1 Experimental set up

Pressure Drop Test Setup

Because of the relatively small diameter of the tubes (1.067mm and 0.62mm) it was difficult to make holes for pressure taps with conventional machining techniques. EDM technique was used to make slits on the surface of the tube that work as the pressure ports. The details of the pressure port design are depicted in the Fig. 2.

For measuring the pressure drop Tee connectors (T2 and T3 type) are used in conjunction with heat shrink tubing (1:4 reduction ratio). The inlet and the outlet Tee's are positioned horizontally and placed over the pressure ports. A pressure transducer (0-5Psi) is used for measuring the pressure drop. The transducer ports are positioned parallel to the Tee connection so that both of them lie in the same horizontal plane and avoid any gravitational effects on the pressure drop readings. Also care is taken to avoid abrupt changes in cross section to avoid expansion and contraction losses.

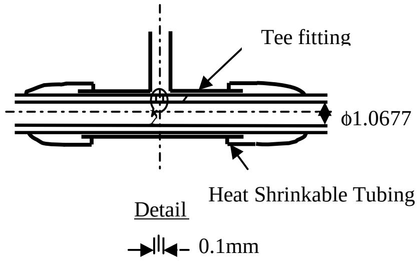


Figure 2 Pressure port design for measuring pressure drop

Table 1 Summary of the Previous Studies on the Effect of Surface Roughness on Heat Transfer and Pressure Drop

Author	**Pfahler, et al. (1991)**	**Rahman and Gui (1993)**	**Harmas et al. (1999)**	**Wu and Little (1983)**	**Wu and Little (1984)**	**Peng and Wang (1994)**
Exptl. Condition	N/A	Re: 100~15000	Re: 173~12900	Re: 100~15000	Re: 400~20000	Re: 50~4000
Channel Geometry	Rectangular, Trapezoidal	Rectangular (I pattern, U pattern)	Rectangular (single & multiple)	Trapezoidal	Trapezoidal	Rectangular
Channel Size(μm)	L= 10.9-10.2mm D=38.7-0.96 W_{rect}= 115-77.5 W_{trap}= 93.7-22.5	L=46mm Width=1mm Depth= 278-176	b= 1000 & 1030 deep W_{ch}= 25000 & 251 wide W_{w}= 119 thick	L=7.6-40.3 (mm) D= 28-65	L=28-30 (mm) D= 89-97	H/W: 0.333~1
Dh (μm)	0.96~39.7	900~3200	1923~404	45.5 ~ 83.1	134 ~ 164	133
Surface Roughness	0.01	Not reported	0~0.020	0.05 ~ 0.30	0.01	Not reported
Test Fluid	Alcohol, silicone oil, isopropanol, nitrogen, helium	Water	Deionized water	N_2, H_2, A_r	N_2	Water
Orientation	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal
Heating Method	Electrical			Not applicable	Liquid nitrogen cooling	Electrical
Re_c	Not studied	Almost same as conventional channel	1500	350 ~ 900	1000 ~ 3000	200
Pressure Drop:	800~470,000k Pa/m	Friction factor: 6.5~23.0	0.925~61.2 kPa (singlechannel) 1.22~169 kPa (multichannel)	1.1-5.0	Not studied	0.47(lam) 0.03(turb)
Heat Transfer: Nu	Not reported	5~34	40.9at Re<1383(lam, single); 44.0~159 at 1700<Re<12900 (lam); 2.65at Re<334(turb, multi); 17.6 at 411<Re<1188 (turb., multi)	Not studied	<1 at Re<650 (lam); >1 at 650<Re<1000(lam); 1.38~ 1.69 (turb)	<1 (lam) 0.41(turb)
Results	For the largest channel size of 40 μm, the result are very good agreement with theoretical predictions.	Nusselt numbers are larger than analytically predicted values using developing flow eqns. The transition from laminar to turbulent flow was somewhat gradual because of small channel dimension, which is of the same order of magnitude as the turbulent length scale.	For fully developed laminar flow the thermal resistance is independent of the pressure drop. Nusselt number was higher than predicted at all flow rates. The thermal resistance of the multiple channel design is always lower than that of the single channel design for a given pressure drop.	The friction factor was influenced by the channel roughness even in laminar flow. The rougher the surface of the channel, the earlier the transition from laminar to turbulent flow.	The average h (based upon the fluid inlet and outlet temperatures) was found to be larger for the channel with heat coming from two sides than for the channel with heating from only one side.	The transition Re decreased with the reduction of the meso-channel dimensions. Laminar: NuμRe$^{0.62}$ Significant effect of H/W, D_h on f, h. Smaller D_h=> lower Re_c and transition range.
Remarks	With increase in inlet pressure and Re, the friction constant increases.	The larger heat transfer is caused by the breakage of velocity boundary layer by surface roughness associated with etched channel structure.	Laminar flow provides better overall performance than turbulent flow.	High relative roughness	Asymmetrically rough surfaces. Data compared to smooth tube correlation for laminar flow. h based on Tin and Tout.	h based on Tin, which could possibly explain the low h except for Dh=240mm.

Heat Transfer Test Setup

Electrical resistance heating of the stainless steel tube is used to heat the water flowing through the tube. The aforementioned pressure port design has a drawback if used for resistance heating since the two legs of Tee connectors served as the low resistance path for the current. Hence separate specimens were designed to carry out heat transfer tests.

For the heat transfer experiments, thermocouples (K-type, -270 to 1372 C) are installed at three sections along the tube length as shown in the Fig. 3. Thermocouples are attached to the tube by using high conductive epoxy to improve the accuracy of measurement. Also care is taken to insulate the thermocouple wires from each other. Direct heating of the tube using two semi-circular copper plates is employed as described below. Two brass cross connectors are used at the inlet and the outlet section of the tube. One leg is occupied by inlet thermocouple measuring the inlet temperature. The other leg of the cross is connected to the pressure transducer. A similar arrangement is used at the outlet of the test section. For the resistance heating, the tube is clamped between two copper plates that are bolted together. Using the EDM technique, a semicircular tube profile is generated over the top and the bottom of the cover plates. This ensures a positive contact between the tube and the copper plates. DC electrical power is supplied to these plates that are in positive contact with the tube. The voltage is measured at the point where the power connections are made. This voltage times the input current gives the net power supplied to the test section. Heat losses through the test section are minimized by wrapping fiberglass insulation around the tube and the fittings.

EXPERIMENTAL PROCEDURE

Pressure Drop Tests

Before readings are taken, the water is allowed to flow through the test section for quite some time so as to make flow steady and very little fluctuations in the pressure drop values are observed. Normally the flow became steady in a few seconds. After these preliminary tests, the data is logged using the LabView program. The data is acquired for approximately 30 seconds for a particular mass flow and is stored in a file. Calibration of pressure transducer and thermocouples is done using LabView interface.

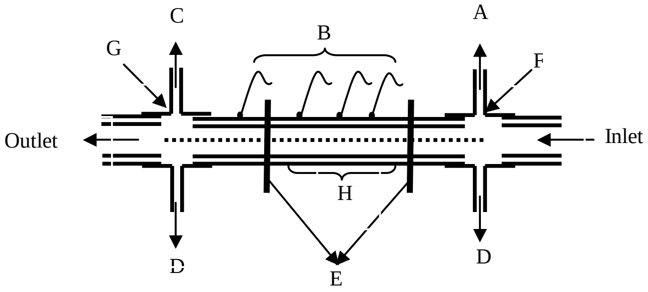
Following readings were recorded,

- Mass flow through the test section
- Pressure drop inside the tube

Heat Transfer Tests

Prior to recording the data, the system is allowed to reach a steady state. Steady state is reached when the energy balance between input power and the energy taken up by water is nearly the same. In some cases, the fluctuations in the flow affected this energy balance, especially in the turbulent region. Once the steady state value is reached, readings of the voltage are taken and the data is acquired for approximately 30sec for every power input. The data is eventually stored in a file as a text. Following readings were recorded:

- Mass flow of the water
- Inlet temperature of the water
- Temperature over the wall of the test section
- Outlet temperature of the water
- Pressure drop in the system
- Voltage across the test section
- Current reading of the power input



A: Inlet Water Temperature Thermocouple
B: Wall Thermocouple at different locations
C: Outlet temperature thermocouple
D: Connection to Pressure Transducer E: Copper Heating Plates
F,G: Brass Cross Connector H: Test Section

Figure 3 Experimental test facility for conducting heat transfer tests

Since the diameter of the tube plays a critical role in the results obtained, the tube was cut in lengths of 3mm (20 pieces) on the EDM (Electrical Discharge machine). The cuts were made ensuring perpendicularity in the cut. After the test specimens are formed, diameter is measured from both the sides of the test pieces using an optical instrument. After recording the diameter from these test pieces an average value for the diameter of the tube is obtained. Similar procedure is used for 0.5mm size tube (as specified by the manufacturer). It was observed that the actual inner diameter of the 0.5mm tube was 0.62mm.

ETCHING TECHNIQUE

Because of the small dimensions of the tube several techniques were tried to change the roughness, but since these small dimension are difficult to access from the inside, acid etching was found to be the preferable alternative. Several chemical reagents were tried to change the roughness of the tube from the inside. The concentrations of the acids used to etch the stainless steel tubes are summarized in Table 2.

Two sets of acid treatments were carried out each on 1.032mm and 0.62mm tubes to change the surface roughness. The tube is filled with acid and allowed to stand for 1 minute before emptying it. This procedure is repeated several times. Filling and withdrawal of the acid is carried out using a medical syringe. After the tubes were acid treated, they were filled with the acid to allow sufficient time for the reaction to take place. Table 2 provides the detail of the above treatments.

Treatments	Compositions	No. of injections **	Soaking Period after treatment (hrs.)
Acid 1	HCl: 8ml HNO_3: 10ml, @Room Temp.	10	2
Acid 2	HCl: 50ml HNO_3: 5ml H_2O: 50ml, @50 C	20	4

Table 2 Table depicting different compositions and treatment time used for etching (**Treatment process consists of injecting the acid and holding it for a minute. This procedure is repeated given by no. of injections in the table)

Sample (Stainless Steel)**	D=1.067 (mm)	D=0.62 (mm)	D=1.067 (mm)	D=0.62 (mm)
	Ra (μm)	Ra (μm)	e/d	
Surface A Original surface	2.4	2.2	0.00225	0.00355
Surface B Treated with Acid Treatment 1	1.9	1.8	0.00178	0.00290
Surface C Treated with Acid Treatment 2	3.0	1.0	0.00281	0.00161

Table 3 Surface roughness values for the 1.067 mm and 0.62 mm diameter tubes after acid treatments

**Surface A: Unetched Sample (Commercial tube)
Surface B: Sample after Acid Treatement-1
Surface C: Sample after Acid Treatement-2

ROUGHNESS MEASUREMENT

Acid treated surfaces are analyzed for the roughness changes. A micrograph of roughness structure is obtained indicating the Ra (average roughness in microns) value over the scanned region. This test being a destructive one, a sample of the tube is cut in two parts and the readings are taken over the length of the sample on both the parts. Later the readings from the two parts are averaged to get the final value of the roughness for that particular treatment. The scanned length of the stylus is 2000 micrometers. Alpha-Step 200 (Tencor instruments) is used for measuring the roughness of the tube. Table 3 gives the measured roughness values for the tubes. In this paper the relative roughness is calculated by taking ratio of the average roughness value over the tube diameter (e/d). This definition is different than the Nikurades's (1933) consideration in which a known grain size is uniformly glued over the surface of the tube to alter the roughness of the tube. This grain size over the tube diameter is defined as the relative roughness (e/d).

After etch treatment of the tubes, photographs of the surface texture using SEM (Scanning Electron Microscope) by Philips Co. are taken to study the effects of etching. The surface texture photographs for 1.067mm and 0.62mm tubes before and after etching are shown in the following figures. The photographs are taken at a tilt angle of 60°. At this angle the microscope has a better gain and signal that produces a good overall scattering of electrons. The magnification for the scans depicted in these figures is 640X.

Figures 4 & 5 represent Surfaces A, which is the unetched sample of 1.067mm and 0.62mm tubes respectively. The appearance of troughs and valleys on the surface contributes to the surface roughness. Both Surfaces A (1.067mm and 0.62mm) show a similar surface pattern. Small globular structures on the surface represent contaminants that are adsorbed on the surface. However attempts were made to remove them using compressed air prior to scanning.

Figs. 6 & 7 represent scans of Surface B for 1.067 mm and 0.62 mm diameter tubes, and Figs. 8 and 9 show the scans for Surface C for these two tubes respectively. Surface B is after acid treaement-1 and surface C is after acid treatement-2. As seen from the scans for Surface B, Figs. 6 and 7, the depth of the valleys is reduced; this can be attributed to the fact that the corrosion causes some of the thin walled 'troughs' to disappear thereby effectively reducing the surface roughness.

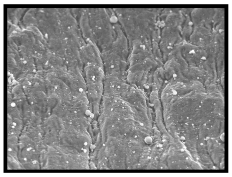


Figure 4 Surface A (1.067mm)

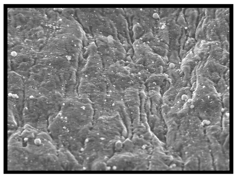


Figure 5 Surface A (0.62mm)

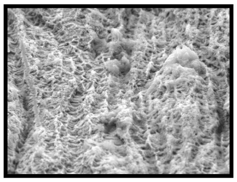


Figure 6 Surface B (1.067mm)

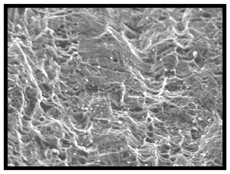


Figure 7 Surface B (0.62mm)

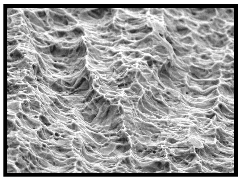


Figure 8 Surface C (1.067mm)

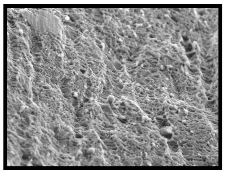


Figure 9 Surface C (0.62mm)

Scanning Electron Micrographs of Tube Surfaces

The effects of Treatment 2 resulting in Surface B are somewhat different for the tubes as seen from Figs. 8 and 9. For the 1.067 mm diameter tube, Surface C in Fig. 8, acid treatment 2 further reduces the troughs, but the corrosion at the valleys penetrates the surface deeper resulting in an increase in the surface roughness value as seen in Table 3. For the 0.62 mm diameter tube, Surface C in Fig. 9, the troughs

Sample Measurements	1.067mm Ra (microns)	0.62mm Ra (microns
Acid-treatment 1: Average Ra = 2.4 for 1.067mm Average Ra = 2.2 for 0.62mm	2.33 2.1 2.77	2.43 2.19 1.98
Acid-treatment 2: Average Ra=1.90 for1.067mm Average Ra= 1.80 for 0.62mm	1.92 1.83 1.95	1.75 1.8 1.85
Acid-treatment 3: Average Ra= 3.0 for 1.067mm Average Ra= 1.0 for 0.62mm	3.10 2.9 3.0	1.06 0.95 0.99

Note: The Sample length is approximately 10mm
Readings are taken approximately 3mm apart

Table 4 : Roughness measurement at different locations on the tube sample for various acid treatments

continue to disappear, while the corrosion rate at the valleys does not induce an equivalent penetration. This results in further smoothening of the tube with a lower roughness value. Table 4 presents the multiple surface roughness measurements carried on a test sample after each acid treatment.

EQUATIONS FOR DATA REDUCTION

For the data reduction following equations are used to calculate the required parameters.

The hydrodynamic entry length is found by,

$$X_h = 0.05 \text{ Re } D_h \qquad (1)$$

The thermal entry length is given by,

$$X_{th} = 0.05 \text{ Re Pr } D_h \qquad (2)$$

The power input to the tube is given by standard equation,

$$P_{in} = V \times I \qquad (3)$$

The amount of energy carried away by the water in the test section is as given by,

$$Q = \dot{m} \times C_p \times (T_o - T_i) \qquad (4)$$

The heat transfer coefficient for the present case is obtained by,

$$q'' = h \times (T_w - T_f) \qquad (5)$$

To find the local heat transfer coefficient, we need to find the temperature drop across the thickness of the tube. Following expression is used to calculate the temperature at the inner tube surface at radius r_1 (inner).

$$T(r_1) = Ts + \frac{\dot{q}}{4k}\left(r_2^2 - r_1^2\right) - \frac{\dot{q}}{2k} r_2^2 \text{Ln}\left(\frac{r_2}{r_1}\right) \qquad (6)$$

The pressure drop inside the tube is given by the following equation,

$$\Delta P = \frac{f \times L \times V^2 \times \rho_m}{2 \times D} \qquad (7)$$

The calculations for the laminar hydrodynamic entry length indicate that the flow is hydrodynamically fully developed at the test section. The test section is therefore under thermally developing flow conditions. The variation of the theoretical local Nusselt number (constant heat flux) along the tube length in the flow direction is obtained from the following equation, (Shah and London, 1978),

$$Nu_x = 4.364 + 8.68 \times (10^3 \times x^*)^{-0.506} \times e^{-41x^*} \qquad (8)$$

UNCERTAINTY ANALYSIS

An uncertainty analysis of the experimental measurements is necessary for the results to be meaningful. All uncertainty evaluations are performed with 95% confidence level. The 95% confidence uncertainty is calculated from,

$$U = \left[B^2 + P^2\right]^2 \qquad (9)$$

The bias limit is an estimate of the magnitude of the fixed error. It is generally considered to be the least count of the measuring instruments, calibration data as supplied by the manufacturer.

The sample calculations at Re=2000 (Surface A, 0.62mm dia.) resulted in an uncertainty of 5% in the local Nusselt Number, and 0.7% in the pressure drop measurements.

RESULTS AND DISCUSSIONS

Heat Transfer Characteristics

The local Nusselt number is calculated at the three locations, one near the inlet, one at the middle, and one near the outlet sections. The positions are measured from the inlet of the heated section (starting from the copper connector) and are given in Table 4.

Tube Diameter (mm)	Near Inlet (mm)	Middle (mm)	Near Outlet (mm)
0.62	37	52	67
1.067	46.5	61.5	76.5

Table 4 Locations of the thermocouples measured from the heated test section

Heat fluxes as high as 116 kW/m^2 and 35 kW/m^2 are obtained for 0.62 mm and for 1.067 mm tubes respectively. The outlet temperature of water being 36°C for both 0.62 mm and 1.067mm tubes for the lowest mass flow rate. In this experiment, the flow is hydrodynamically fully developed while it is in the thermally developing region. The velocity and thermal entry lengths are calculated using eqs. (1) and (2) respectively. The fully developed hydrodynamic entry length is 57 mm and the thermal development length is 380 mm for 0.62 mm and 115 and 760 mm for 1.067 mm tube at 2300 Reynolds number.

Figs. 10, 11 and 12 present the local Nusselt number values near the inlet, mid and outlet of the heated test section plotted as a function of Reynolds number for 1.067 mm tube in the thermally developing region. The effect of surface roughness on heat transfer is insignificant and falls within the error limit. In all these figures, the Nu vs. Re slope increases at around 2300. This is believed to be due to transition to turbulent flow since the wall temperatures were maintained below the saturation value to avoid localized boiling.

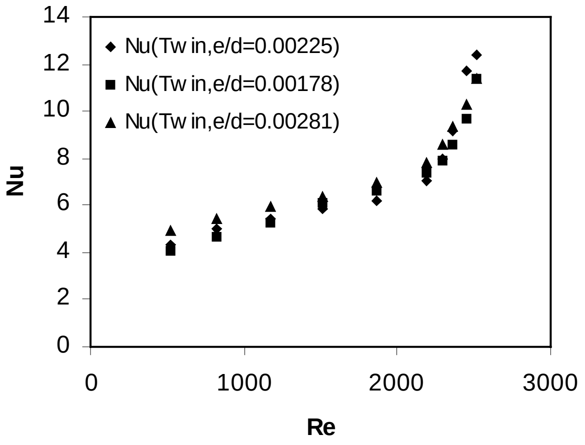


Figure 10 Plots of local Inlet Nusselt number for different e/d ratios (1.067mm dia. tube)

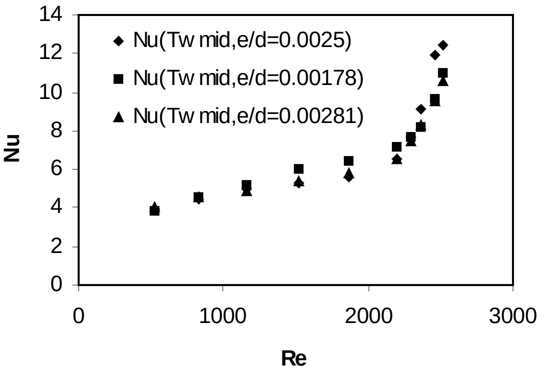


Figure 11 Plots of local Nusselt number at the middle for different e/d ratios (1.067mm dia. tube)

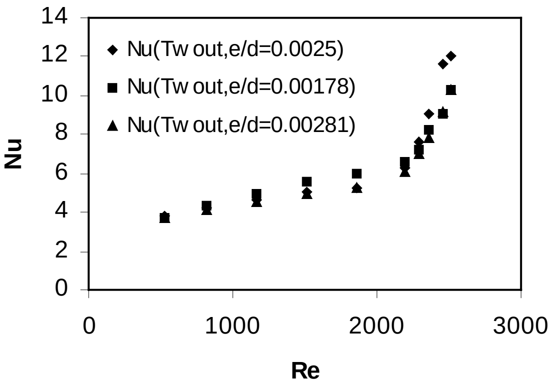


Figure 12 Plots of local outlet Nusselt number for different e/d ratios (1.067mm dia. tube)

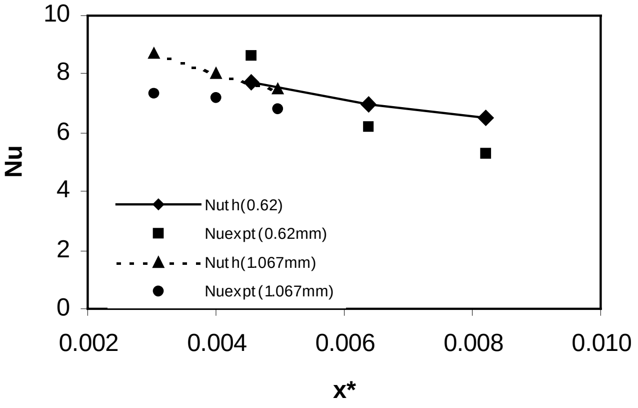


Figure 13 Comparison of theoretical Nusselt number against experimental values along the length

The experimental values of the local Nusselt number in the entry region are compared with the correlation given by eq. (8) for Re=2000 and e/d=0.00178 for 1.067 mm tube and e/d= 0.0029 for 0.62 mm tube. It is observed from the Fig. 13 that the theoretical values obtained are slightly higher than the experimental results for both 1.067 mm and 0.62 mm tube.

Figs. 14, 15 and 16 show the effect of surface roughness on the local Nusselt number at the inlet, mid and outlet of the heated test section for the 0.62mm tube. The flow is in the thermally developing region. It is observed that with an increase in the relative roughness, there is a significant change in the heat transfer characteristics compared to that for 1.067mm tube. It is seen that the commercial tube is rough (higher e/d) and exhibits higher heat transfer compared to the other two with acid treatments 1 and 2. The effect of roughness for 0.62mm tube is also seen in the laminar region as observed from local Nusselt number plots. It is also seen that in both 1.067mm 0.62mm tube there is a steep rise in Nusselt number. This is because the flow may be in the transition region or the turbulent region (Re>2300). Also for the high flow rates the temperature difference is small that accounts for very high heat transfer coefficients.

Hence from the above results, the effect of roughness is insignificant in the case of 1.067mm tube, while for 0.62 mm diameter tube, surface roughness above e/D of 0.003 results an increase in the heat transfer and pressure drop values. Hence it could be stated that for small diameter tubes, the effect of surface roughness has a larger impact on the heat transfer characteristics.

Pressure drop Characteristics

The same etching technique is used to produce the tubes for pressure drop tests. Sample roughness measurements with tubes that are similarly treated yielded almost identical values. Hence similar roughness values were considered appropriate for pressure drop test specimens. The flow is hydrodynamically fully developed before it enters the heated section.

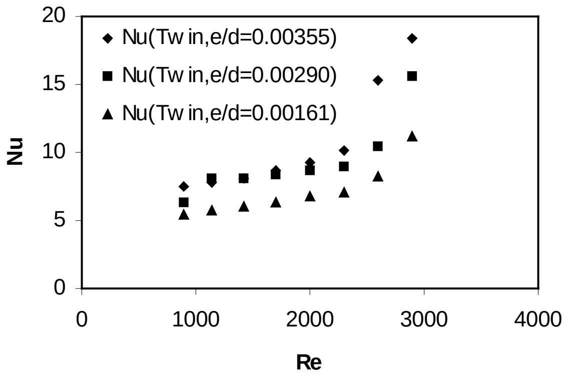


Figure 14 Plots of local Inlet Nusselt number for different e/d ratios (0.62mm dia. tube)

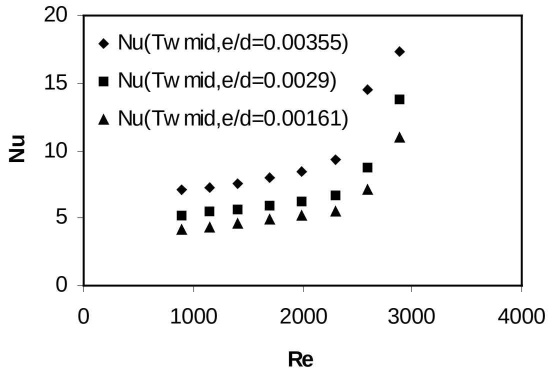


Figure 15 Plots of local Nusselt number at the middle for different e/d ratio (0.62mm dia. tube)

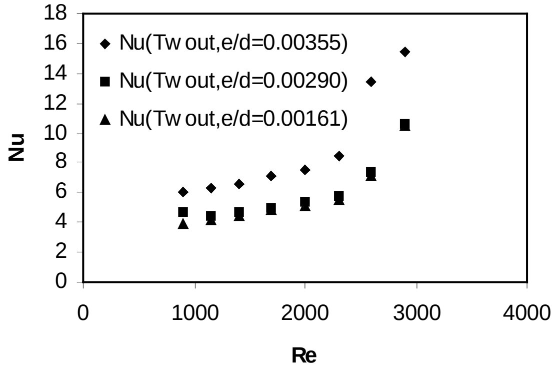


Figure16 Plots of local outlet Nusselt number for different e/d ratios (0.62mm dia. tube) **Figure16 Plots of local outlet Nusselt number for different e/d ratios (0.62mm dia. tube)**

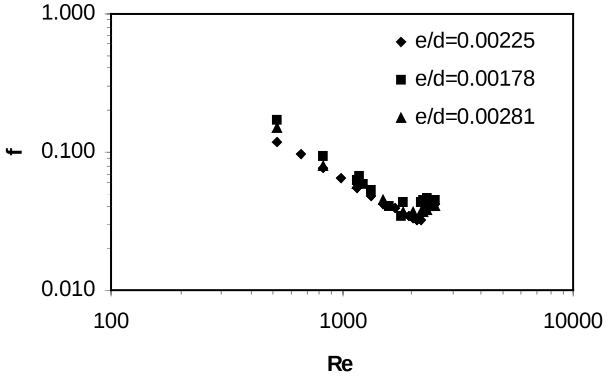


Figure 17 Graph of friction factor against Reynolds number for different e/d ratio (1.067mm dia. tube)

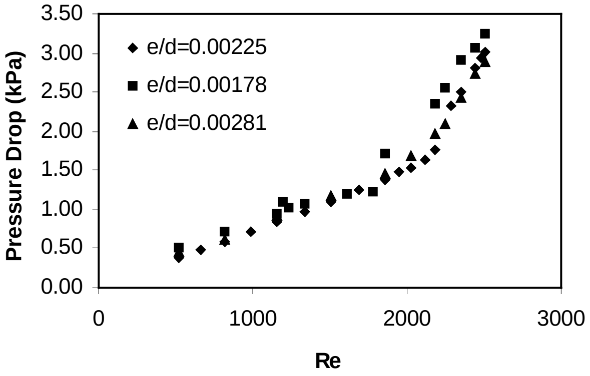


Figure 18 Graph of Pressure drop against Reynolds number for different e/d ratio (1.067mm dia tube)

Figures 17 and 18 present the effect of surface roughness on pressure drop and friction factor for 1.067mm diameter tube. As seen from these figures, pressure drop increases with an increase in Reynolds number as expected. The pressure drop and friction factor variation follow a similar trend as the heat transfer plots. The effect of surface roughness is negligible and falls within the error band. The transition Reynolds number is around 2300.

Figures 19 and 20 represent the variation of pressure drop and friction factor with Reynolds number for 0.62mm tube. It is seen that both acid treatments make the tube smoother than the commercial (unetched) tube. A reduction in the relative roughness results in decreasing pressure drop values as well as decreasing friction factor values. This trend is in agreement with the heat transfer results discussed earlier. The transition Reynolds numbers for Surface A is lower than 2300. Hence for the 0.62 mm diameter tube the effect of surface roughness is significant compared to 1.067 mm tube

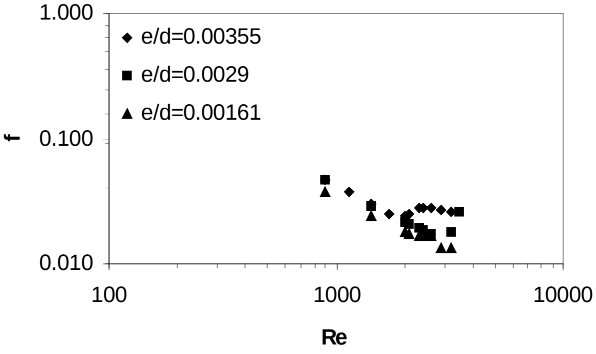


Figure 19 Graph of friction factor against Reynolds for number for different e/d ratios (0.62mm dia. tube)

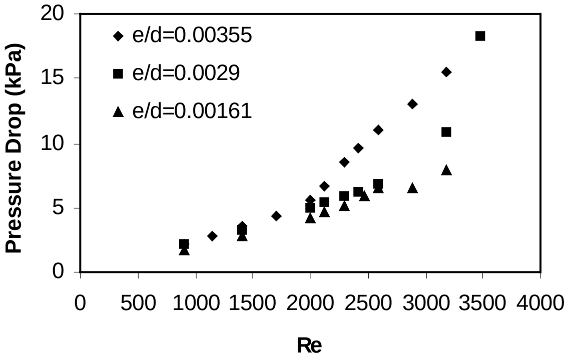


Figure 20 Graph of Pressure drop against Reynolds number for different e/d ratio (0.62mm dia tube)

CONCLUSIONS

Some of the major conclusions from the paper are summarized below:

- The roughness values of the commercial 316 stainless steel tube of 1.067mm and 0.62mm diameter are altered by using different acid treatments. It is observed that with different acid treatments, tube gets smoother first, and then becomes rougher after prolonged acid treatment.
- The experimental values of local Nusselt number are compared with theoretical correlation in the thermal entry region of a hydrodynamically fully developed flow. It is seen that the agreement is within the experimental results.
- For 1.067 mm diameter tube, the effect of varying the roughness from e/D=0.00178 to 0.00225 on heat and pressure drop are insignificant.
- For 0.62mm tube, the heat transfer and pressure drop results show dependence on the surface roughness. Commercial tube with higher e/d (=0.00355) yielded the highest heat transfer and pressure drop values; subsequent acid treatments made the tube smoother and yielded lower values of heat transfer coefficient and pressure drop values.
- Large diameter tubes, above 1.067mm with e/d=0.003, may be considered as smooth tubes. However for small diameter tubes (<0.62 mm) the same roughness value increases the heat transfer and pressure drop characteristics. The transition to turbulence also gets affected by changing the roughness values above this limit for the small diameter tubes.
- Further research on small diameter tubes below 0.62 mm all the way to 0.1 mm is recommended.

ACKNOWLEDGEMENTS

The authors are grateful to the support extended by the Department of Industrial Engineering., Material Science, and Microelectronics Engineering for allowing the use of different equipment in their laboratory. We also acknowledge all the personnel (Josh, Industrial Engineering., Dr. Santosh Kurinec, Associate Professor, Microelectronic Engineering., and Ms. Pranita Kulkarni, Graduate Student, Material Science Program, at RIT) in these departments for helping us with this project.

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