# Numerical Investigation of Laminar Flow in Micro-tubes with Designed Surface Roughness

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**Abstract** Recently, there has been a rapid growth in applications that deal with fluid flow at micro-scale where surface roughness is a real feature in these applications. Published literature shows conflicting findings regarding the effect of surface roughness on the friction factor of laminar flow at micro-scale. The understanding of fluid flow behavior in micro-tubes is very important for effective design of micro-fluidic devices. This work presents a numerical investigation of the effect of various surface roughness geometries on friction factor in fluid flow in the laminar regime. Results indicate that surface roughness causes deviation of the frictional factor from conventional theory with various values depending on the height and shape of the roughness used.

**Keywords:** Surface roughness, Micro-channels, CFD, Fluent.

## 1. Introduction

In recent years, interest in micro-fluidic systems has seen significant expansion due to the rapid growth in applications that deal with fluids at the micro-scale. Such applications include: micro-total analysis systems (μ-TAS) used for medical diagnostics, chemical and biological analysis, genetic analysis, drug screening (Velten et al., 2005), and cooling for high power electronic devices (Mudawar, 2000). The understanding of fluid flow behaviour in micro-channels is very important for the effective design of micro-fluidic devices (Morini, 2004a). Generally the classical Navier-Stokes equations, developed for conventional fluid flow, are used to predict pressure drop in micro-channels. However, published experimental work for single phase laminar flow in micro-channels has shown significant deviation from these predictions (Morini, 2004b). Several justifications have been proposed in the literature to account for this deviation, like: surface roughness (Qu et al., 2000) and variation of fluid properties (Toh et al., 2002). Surface roughness is a real feature in most micro-fluidic devices; it takes many different shapes, depending on the micro-fabrication process, the materials used and in some cases by adhesion of biological particles from the working fluids. With the increased surface to volume ratio in micro-channels, and surface roughness height being comparable with channel dimensions, the presence of surface roughness becomes more significant.

Several published experimental and numerical data has shown contradictory results regarding the effect of surface roughness on friction factor, and whether the laminar flow behaviour in micro-channels is governed by conventional flow theory. Sharp et al. (2004) carried out a series of extensive experiments using glass micro-tubes with diameters ranging from 50 to 247μm. Liquids with different polarities were used and *Re* number varied from 50 to 2500. Bulk flow measurements using micro-particle imaging velocimetry (μPIV) were used. Results indicate clear good agreement with the laminar conventional solution. Li et al. (2003) studied frictional resistance for deionized water laminar flow through smooth and rough micro-tubes. Glass, silicon and stainless steel micro-tubes were used with diameters ranged from 79.9 to 205.3μm. Stainless steel tubes came with a relative surface roughness, $\varepsilon/D$, values of 0.03 to 0.04. Experimental results showed that for the smooth tubes, the Hagen-Poisuelle number, *f.Re*, remained very close to conventional value of 64, the value used for macro-tubes laminar flow analysis. As for the stainless steel micro-tubes, the Hagen-Poiseuille number was found to be 15-37% *higher than* 16, a finding that contradicts the conventional theory, which assumes that relative surface roughness below 0.05 has no effects on laminar flow characteristics.

Many researchers have used computational fluid dynamics techniques to investigate the effect of surface roughness on laminar fluid flow in micro-channels. Yandong et al. (2003) developed a 3D finite-volume-based numerical model to simulate pressure-driven liquid flow in micro-channels with rectangular prism rough elements on the surfaces. Their numerical solution showed significant effects of surface roughness in terms of the rough elements' height, size, spacing, and the channel height on both the velocity distribution and the pressure drop. Giulio et al. (2005) modelled surface roughness as a set of randomly generated peaks along the ideal smooth surface, different peak shapes and distributions were considered; with geometrical parameters representative of tubes in the diameter range from 50 to 150μm. Results for laminar flow (Re up to 1600) showed significant increase in Poiseuille number for all the configurations considered. Giulio et al. (2007) modelled roughness is as a set of 3D conical peaks distributed on the ideal smooth surfaces of a plane micro-channel. Different peak heights and different peak arrangements were considered at various Reynolds numbers. Results showed a remarkable effect of roughness on pressure drop.

Haoli et al. (2007) investigated the influences of 3D wall roughness on the laminar flow in micro-tube. Roughness was modelled using two-dimensional simple harmonic function that’s axial and azimuthal wave numbers are alterable. Numerical results showed pressure drops were about 0-65% higher than that of Hagen-Poiseuille flow on condition that the relative roughness increases from 0 to 0.05. Rawool et al. (2005) carried out a 3D numerical simulation for flow through serpentine micro-channels with designed roughness in the form of obstructions placed along the channels walls. The effect of the roughness height, geometry, and Reynolds number on the friction factor was investigated. It was found that the friction factor increases in a nonlinear fashion with the increase in obstruction height. Zhang et al. (2010) numerically analyzed the effect of roughness elements height and spacing on pressure drop in micro-channels. Rough surfaces were configured with triangular, rectangular and semicircular roughness elements, respectively. Results indicated that the Poiseuille number was no longer constant with Reynolds numbers and was larger than the classical value.

Xiong (2011) numerically investigated the water flow through trapezoidal silicon micro-channels with hydraulic diameters $D$ from 47 $\mu$m to 241 $\mu$m. The top and side walls were set to be smooth. The effects of Reynolds number Re (75–600), relative roughness height $\varepsilon/D$ (1.66–5.39%), on the Poiseuille number were investigated. It was found that the roughness strongly affects the flow near the bottom wall but does not have significant effect on the centre flow. The Poiseuille number in the developing flow region increases with the Re number and in the fully developed region tends to be independent of the Re number. Bavière et al. (2006) carried out numerical modelling for laminar flows in rough-wall micro-channels using rectangular prism rough elements in periodical arrays. The numerical results confirmed that the flow is independent of the Reynolds number in the range 1–200.

Xiong et al. (2010) proposed a novel bottom-up approach to generate a three-dimensional micro-tube surface with random roughness. The approach starts from four corner points with two defined coordinates and roughness height created by a Gaussian number generator, and then uses a bi-cubic Coons patch to form the curved surface. It was found that the wall roughness strongly affects the velocity near the wall and it almost had no effect on the flow at the centre. When the mean diameter of a rough micro-tube was used as the hydraulic diameter, the friction factor can still be predicted by the conventional flow theory.

This work presents a numerical investigation of laminar flow through micro-tubes with designed surface roughness which takes the form of obstructions distributed along the tube walls. The effects of roughness geometry (square, triangular, trapezoidal and semicircular), height, pitch, and Reynolds number on the friction factor are investigated.

## 2. Methodology

Numerical investigation of the problem has been performed using the finite-volume Computational Fluid Dynamics (CFD) package FLUENT. Coupling between velocity and pressure is resolved by using the SIMPLE algorithm. A second order upwind descritization scheme is used to interpolate the unknown cell interface values required for the modelling of convection terms. No-slip conditions for velocity components and zero normal pressure gradients are set as the boundary conditions for solid walls. The flow domain consists of two parts, the smooth part to ensure fully developed flow and the roughened part. The computational domain was discretized using structured non-uniform rectangular cells for the smooth entry section and the square geometry for the surface roughness. For the trapezoidal, triangular and half circular shaped roughness, unstructured triangular mesh was used. Fig. 1 shows the four surface roughness geometries investigated with the variable mesh densities used where the mesh density near the wall is four times that of the mesh density at the center of the flow.

The height of the surface roughness geometries used was 6.5μm while the pitch varies as shown in Fig. 1. For the surface roughness geometries used, the friction factor was calculated at various Reynolds numbers up to 1200. The effect of tube diameter on the friction factor was investigated for diameters up to 700 μm. Also, the effect of increasing the pitch on friction factor for the square geometry was investigated.

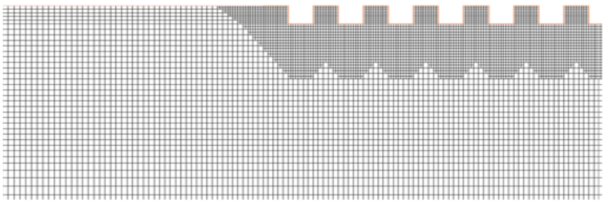
The coefficient of friction, *f*, was calculated according to Darcy-Weisbach Equation as:

$$f = -\frac{dP}{dz}\frac{2D}{\rho U^2} \qquad (1)$$

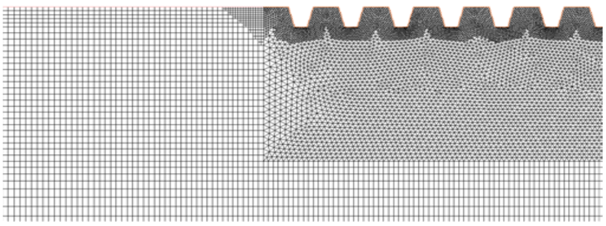
Where $dP/dz$ is the axial pressure gradient, $D$ is the uniform pipe diameter, $\rho$ is the water density, and $U$ is the average velocity at the fully developed part of the smooth tube. For fully developed laminar flow in a macro scale tube, Eq. (1) can be shown to be:

$$f = 64/\text{Re} \qquad (2)$$

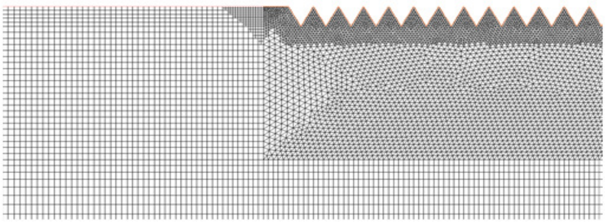
where Re is the Reynolds number based on smooth section diameter and average flow velocity.



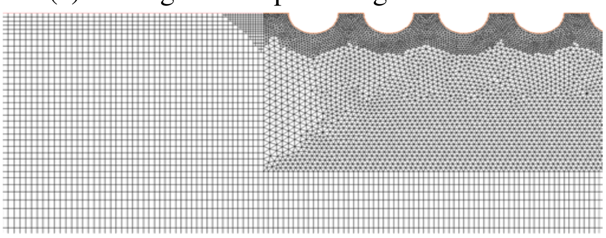
(a) Square-Shaped Roughness



(b) Trapezoidal-Shaped Roughness



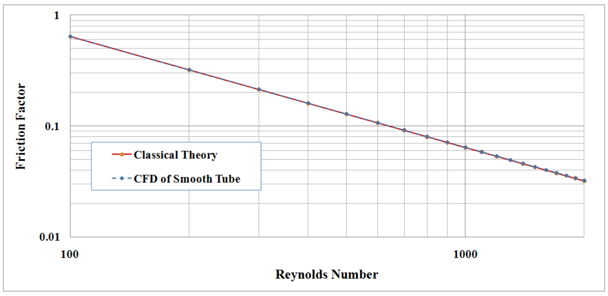
(c) Triangular-Shaped Roughness



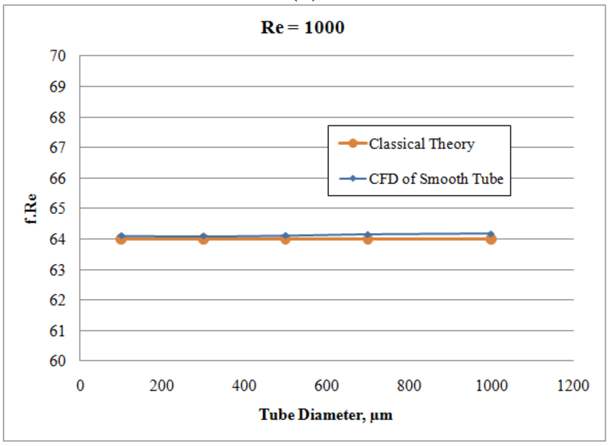
(d) Semi-Circle-Shaped Roughness

**Fig. 1.** Mesh Configuration for the used roughness-shaped geometries

Fig. 2a shows good agreement of the friction factor from the CFD and that of Eq. 2. Fig. 2b shows that for all diameters used, similar values for Poiseuille number from CFD and the classical value of 64. Results shown in Fig. 2 indicate the validity of the methodology used.




(a)




(b)

**Fig. 2.** Friction factor and Poiseuille number for the smooth part compared to conventional theory.

## 3. Results

Fig. 3 shows the velocity contours variation with Reynolds number for different roughness shapes. It can be seen that as the Reynolds number increases the intensity of circulation in the wall cavities increases.

Fig. 4 shows the variation of Poisuell's number (*f.Re*) for the four tested geometries for a roughness height of 6.5µm and tube diameter of 100µm in the laminar range. It can be shown that the Poiseuille number for all investigated geometries is higher than the 64 value stated by the conventional theory which indicates that surface roughness affects the flow behavior of laminar flow in micro-tubes. Also different shapes can produce different values of Poiseuille number with the square surface roughness producing the highest value and the semi-circular producing the lowest value.

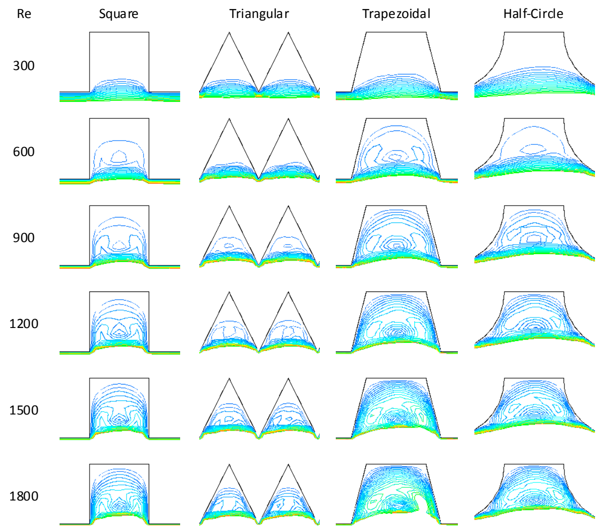



**Fig. 3.** Velocity Contours in roughness cavities

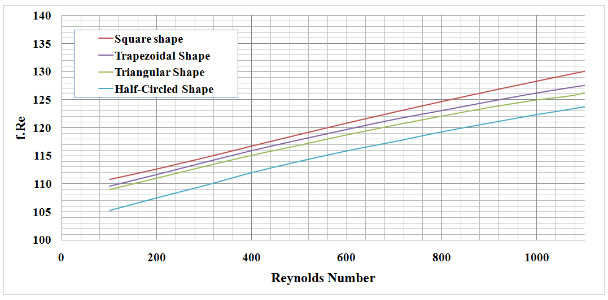
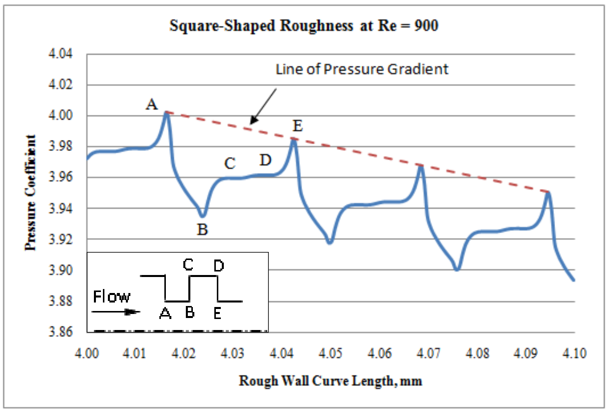
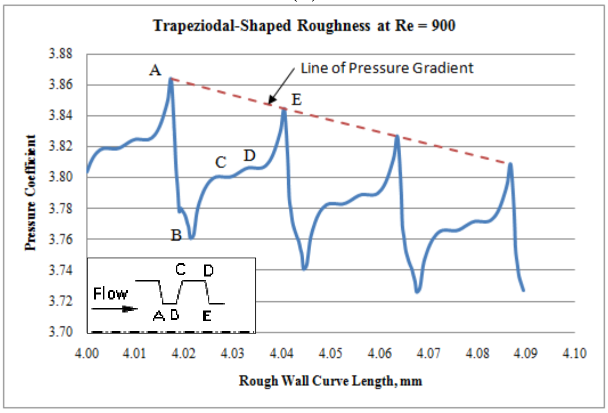



**Fig. 4.** Poisuelle's number versus Reynolds number

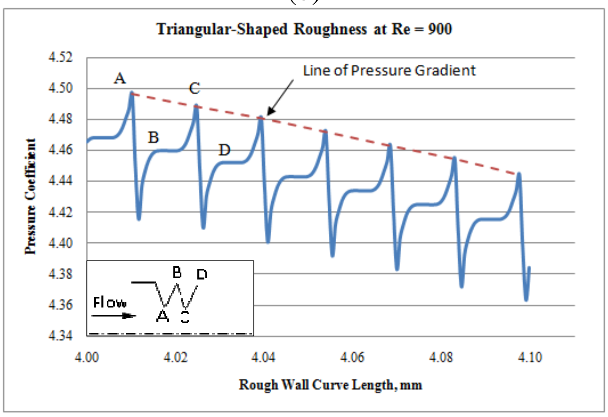
Fig. 5 shows the variation of pressure coefficient along the rough wall of various roughness shapes at Reynolds number of 900 and tube diameter of 100 µm. The pressure coefficient was defined as the fractional change in pressure from the smooth tube inlet value to the dynamic head at the inlet to the smooth section. The wall curve length denoted by ABCDE represents rough wall surface length for one pitch. The dashed line in each figure shows the pressure drop in the relevant geometry. The square-shaped roughness shows the highest axial average frictional pressure drop of 56.95 kPa/mm while the semi-circular shaped roughness exhibits the lowest value of 54.39 kPa/mm.



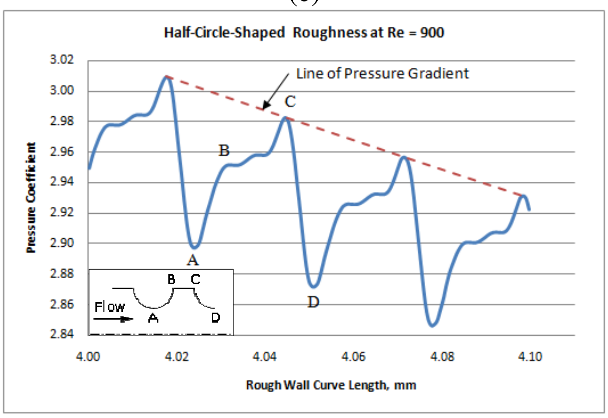

(a)




(b)




(c)




(d)

**Fig. 5.** Pressure coefficient versus rough wall curve length at Re = 900

Fig. 6 shows the effect of increasing the relative surface roughness $\varepsilon/D$ on the Poiseuille number for the geometries used compared to the conventional theory at Re =1000. It is clear that as the value of the relative roughness decreases, the Poiseuille number approaches the conventional theory value. The figure shows that the square geometry produces the highest frictional losses compared to the other geometries, which is consistent with the results shown in Fig. 4.

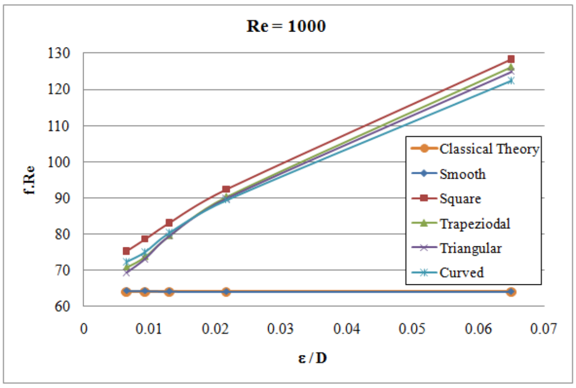



**Fig. 6.** Variation of Poiseuille number with the tube diameter at Re=1000

The effect of increasing the pitch on the friction factor for the square geometry was investigated. Figs. 7 and 8 show the flow contours and the friction factor for the pitches of 13, 26 and 39µm. It is clear that as the pitch increases, the friction factor decreases due to reduced contact area between the fluid and wall.

## 4. Conclusions

A numerical investigation of the effect of various surface roughness geometries (square, trapezoidal, triangular and half circular) on fluid flow in the laminar regime was carried out and the following conclusions can be made:

The frictional factors for all the geometries investigated deviate from the conventional theory which indicates that surface roughness in micro-tubes has an important effect on the flow behavior.

The predicted deviation in the friction factor values depend on the height and geometry of the roughness used with the square shaped surface roughness producing the highest deviation. Also, the effect of roughness on the flow decreases as the relative roughness decreases while increasing the roughness pitch decreases the frictional losses.

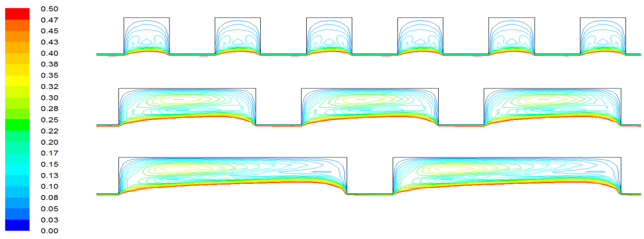


**Fig. 7.** Effect of pitch on velocity contours (m/s) for the square-shaped roughness at Re = 900

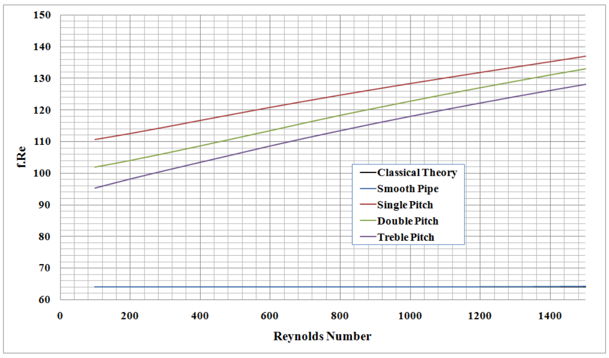



**Fig. 8.** Effect of pitch on friction factor for the square-shaped roughness

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