

EFFECT OF INNER SURFACE ROUGHNESS ON PRESSURE DROP IN A SMALL DIAMETER PIPE

¹Goziya W. Dzarma, ²Adekola B. Adeyemi, ³Abdulmalik A. Taj-Liad

¹Michael Okpara University of Agriculture, Abia State, Nigeria

²MSCM-PPNL Subsea Solution Nigeria Ltd, Rivers State, Nigeria

³Anderson and Dake Nigeria Ltd, Lagos State, Nigeria

Abstract: Surface roughness increases the pressure drop of the flow in a large pipe, as it has been established in literature, however, little is known about pipes with smaller diameters. This work studies the effect of the surface roughness on the pressure drop in pipes with smaller diameters. The pipe considered has ID of 2.3mm, OD of 5mm and a length of 135mm. The numerical analysis was performed using the ANSYS FLUENT software and the roughness on the pipe was modelled as a sphere with a size of 1 μ m. Two different cases were considered for the analysis; when the pipe was smooth and when the pipe was rough. The results showed there was a higher pressure drop in the rough pipe than in the smooth pipe. In addition, the size of the roughness was then increased for 1,5,10,50,100 and 200 microns, and the result shows that as the roughness size increased the pressure drop also increases.

Keywords: ANSYS, CFD, FLUENT, laminar flow, pipe, Pressure drop, surface roughness, small diameter.

I. INTRODUCTION

In recent times, the study of flow in micro-channels have attracted attention of researchers. Many investigations focused on the effects of pipe wall roughness and it has been observed to be present in pipelines as a result of etching, laser drilling and machining process(1). The presence of wall roughness in small diameter pipes has significant bearing on the pressure drop of the fluid flowing in such pipes. Small diameter pipes finds application in many systems because of the enhancements they provide coefficient of heat transfers with very high surface to volume ratios making them highly applicable in cooling systems(2,3). Several studies have been conducted in recent past times with a sole aim of determining the flow characteristics and heat transfer pattern in small diameter tubes, which the findings reveal that they differ with those in pipes with larger diameter.

Peng et al studied the heat transfer and fluid flow patterns in rectangular micro-channels with diameters between 0.1mm and 0.3mm experimentally. The study considered water to be the working fluid and the result showed the micro-channels are hydro-dynamically different from conventional theories(4). Mala et al.(5), using micro-tubes with diameters ranging from 50 microns and 254 microns also conducted an experimental study. Their findings revealed a deviation of flow features from the conventional theories. Their findings also showed a higher value of friction factor compared to that which conventional theory reported. The experimental result showed the transition between laminar and turbulent flow occurs at Reynolds number between 300-900. In another experimental investigation conducted by Yang and Lin(6), it was reported that there is a negligible size effect for water flows in tubes with diameters in the range of 123 microns and 962 microns. The properties of nitrogen flow in small diameter tubes was investigated experimentally by Zhao et al.(7), the results of the experiment indicated that the flow characteristics notably deviated from the classical Poiseuille's theory.

Hasan et al conducted a numerical simulation and drew a conclusion that Reynolds number, thermal conductivity and hydraulic diameter alter the axial conductive transfer(8). Mounir et al (9) conducted a study on the effect of surface roughness on fluid flow and heat transfer using computational fluid dynamics (CFD) software. The model was created with tooth-like structures of the same size and were equally spaced on the inner walls of the small diameter pipeline. The findings were compared with results from a smooth pipe models and there was a noted variation between the two results.

This study used the ANSYS FLUENT software to model the pipe and also the surface roughness. The next section will give a theoretical background to the modelling of inner surface roughness and the calculation of pressure drop in a pipe. The physical modelling and the Numerical modelling will be explained in detail.

II. THEORETICAL BACKGROUND

A. Friction Factor and Roughness

Pressure drop in pipeline with rough surfaces can be attributed to friction and can be evaluated using the friction factor and the Darcy-Weisbach equation given as:

$$\frac{dP}{dL_{fric}} = \frac{f\rho V^2}{2g_c D} \quad (1)$$

Where dP/dL_{fric} is the pressure gradient, f is the friction factor, ρ is the fluid density, D is the diameter of the pipe and g_c is the gravitational conversion factor(10).

The friction factor varies with flow region and the friction factor for laminar flow region is evaluated using the equation below:

$$f = \frac{64}{Re} \quad (2)$$

Where Re is the Reynolds number.

For turbulent regions of flow, Fogarasi recorded that the friction factor can be derived from one of the three mathematical equations:

1. For smooth pipes, Nikuradse equation is applied and is given as:

$$\left(\frac{1}{f}\right)^{0.5} = 2\log\left(\frac{Re f^{0.5}}{2.51}\right) \quad (3)$$

2. For rough pipes, von Karman equation is used:

$$\left(\frac{1}{f}\right)^{0.5} = 2\log\left(\frac{3.7}{\epsilon/D}\right) \quad (4)$$

3. For the transition zone, the Colebrook equation applies:

$$\left(\frac{1}{f}\right)^{0.5} = -2\log\left(\frac{\epsilon/D}{0.37} + \frac{2.51}{Re f^{0.5}}\right) \quad (5)$$

Where ϵ is the grain roughness size and the parameter ϵ/D is the relative roughness of a given a pipe.

B. Characterization of Surfaces

For any given flow path, the roughness trend on the surface and the resulting deviation in the local diameter are given key consideration. In the characterization of surface roughness traits and its effects of fluid flow, three (3) key parameters are considered. These three parameters provide an insight on the roughness traits which include maximum profile peak height R_p , average space between profile irregularities R_{sm} , and the floor distance to mean line F_p . The parameters R_p and R_{sm} are contained in ASME B46.1-2002 (Ref 10) (11) while the F_p was proposed by Kandlikar(12).

1. Maximum peak height (R_p) defines the distance between the highest point of the profile and the average line within the evaluation length

2. Average spacing of the profile irregularities (R_{sm}) measures the average spacing between irregularities within the evaluation length.

$$R_{sm} = \frac{1}{n} \sum_{i=1}^n S_{mi} \quad (6)$$

3. Floor distance to mean line F_p measures the distance between main profile and the mean line.

The three parameters defined above are shown in Fig 1.

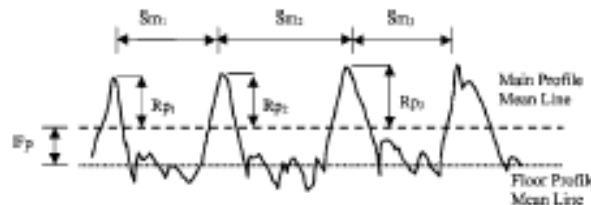


Figure 1: Maximum profile peak height R_p , mean spacing of profile irregularities

These roughness parameters define the features of roughness of a given surface that plays a role in the position and the form of streamlines, and by extension the size of the circulation flow region between roughness elements. These roughness parameters allow for the determination of equivalent roughness, which is estimated using the relationship below:

$$\epsilon = R_p + F_p \quad (7)$$

III. METHODOLOGY

A. Physical Model

The model used for this study was done using the modelling capability of the ANSYS DesignModeler. The ANSYS DesignModeler application is a parametric feature-based modeler designed for intuitive and quick drawing of 2D sketches, modelling 3D parts, or uploading 3D CAD models for engineering analysis application.

The geometry studied in this work is a circular micro channel, the properties of the pipe were obtained from online catalogue of the SHIMANO brakes manufacturer. Two configurations of the brake line have been studied; a smooth pipe without roughness and a pipe with an inner rough surface. The roughness of the inner surface is modelled like a spherical ball embedded in the wall of the inner surface. The section of the pipeline is shown in fig 2.

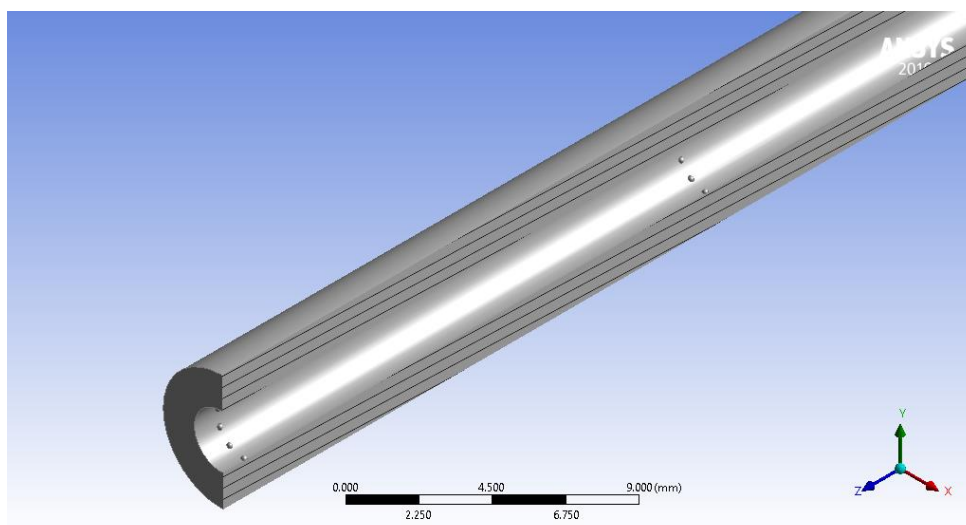


Figure 2: Section of the Pipe Geometry

The pipe geometric properties are summarized in table 1

Table 1: Geometric Properties of Pipe

Geometric properties of pipe	
Outer pipe diameter	5mm
Inner pipe diameter	2.3mm
Length of pipe	135mm
Pipe material	Steel
Density	8030kg/m ³

B. Numerical Modelling

ANSYS FLUENT is used to carry out the numerical modelling of this study. A typical SHIMANO brake line is considered, and the parameters of the brake line was obtained online. The ANSYS FLUENT solution is based on finite volume method. The Simple algorithm was used for pressure-velocity coupling, a second order upwind scheme was used for the discretization of the smooth face and a first-order upwind scheme was employed for the rough case. The convergence criteria for all residues is 10^{-3} .

Mesh

The model had to be simplified for the computer used in running this analysis, in order to be able to run the meshing for the pipe. The rough surface had to be spaced at a distance of 20mm along the pipe for 5 instances and a maximum of 10 spheres were arrayed round the pipe, hence, total spheres on the pipe were 60 balls. The meshing is the most critical part of the analysis as it requires a very high computing power and takes significant time to generate.

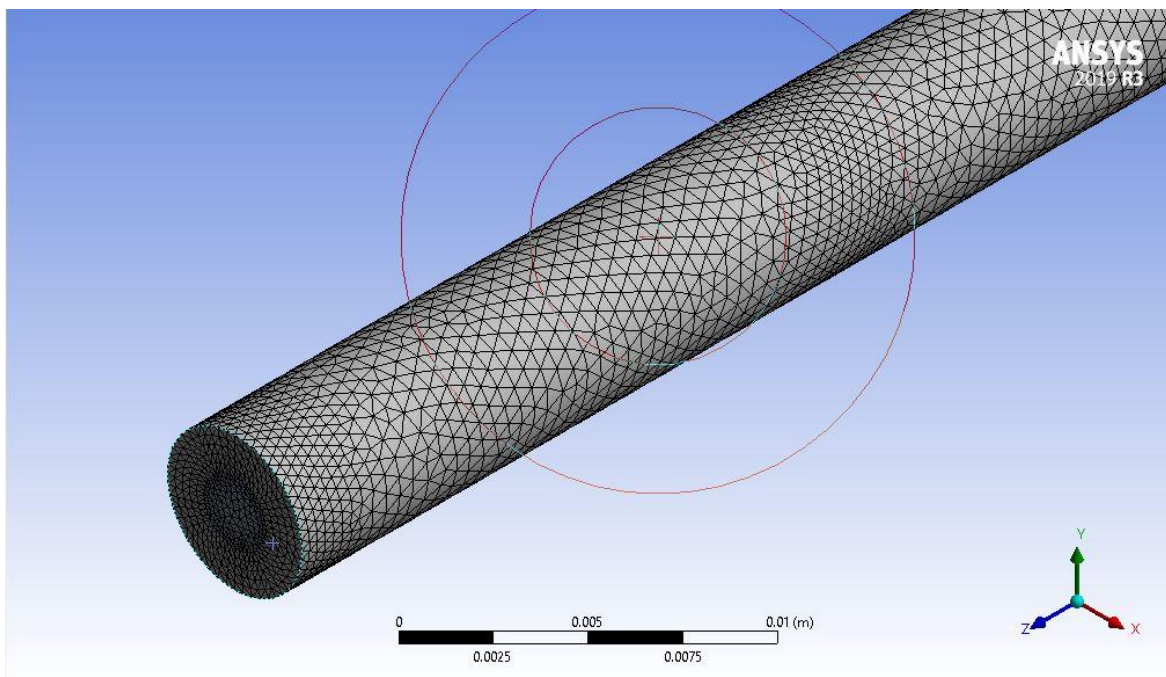


Figure 3: Part of the Pipe Showing the Mesh

The generated mesh in (fig 3) consist of edge sizing and mapped face meshing (fig 4) for equal distribution of cells over the face.

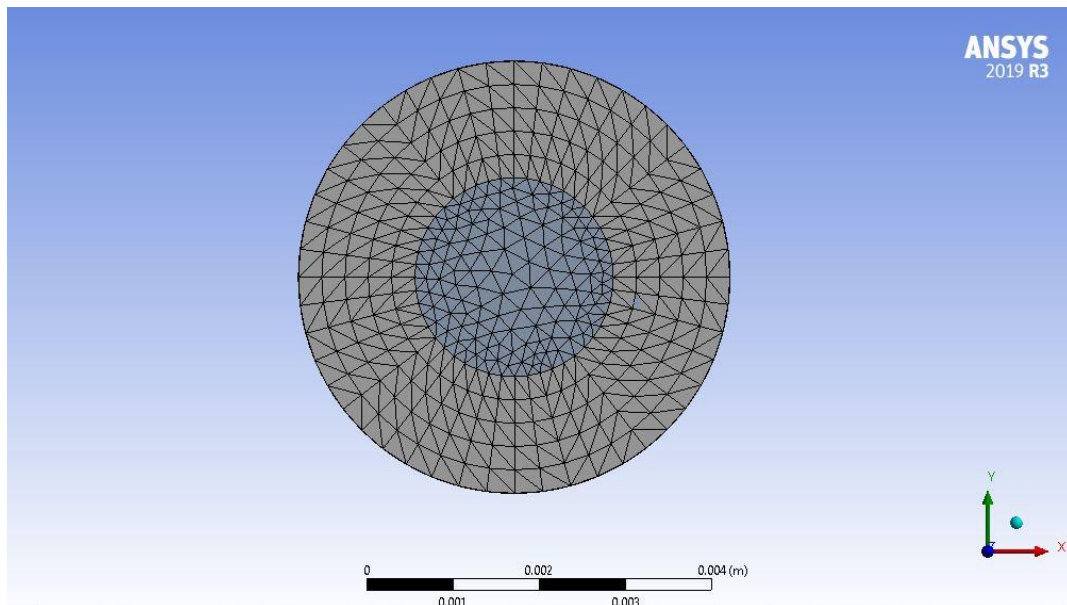


Figure 4: MESH

C. Boundary Conditions

A typical SHIMANO brake line is considered in this study having hydraulic fluid (ethylene glycol) flow through the pipe. At the input of the pipe, a velocity-inlet boundary condition is applied, a velocity of 1m/s is applied based on the Reynold number chosen for the laminar flow. At the output end of the pipe an outflow boundary condition is applied to allow FLUENT determine the output velocity and pressure.

IV. RESULTS AND DISCUSSION

The analysis for the effect of inner surface roughness on pressure drop in a single-phase flow has been studied. The effect of the roughness was determined by comparing the rough pipe result with a smooth pipe result.

Velocity Profile of Flow.

The two pipes were subjected to the same boundary conditions with an initial velocity of 1m/s. at the initial stage the flow was still developing for the smooth pipe and then later got fully developed as shown in Fig 5. A velocity contour plot of the flow is shown in fig 6..

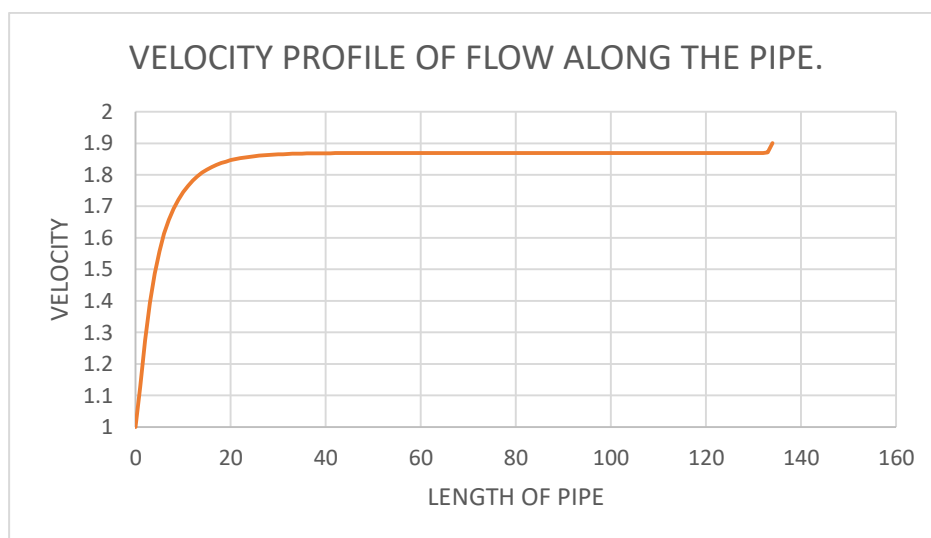


Figure 5: Velocity Profile of the Smooth Pipe

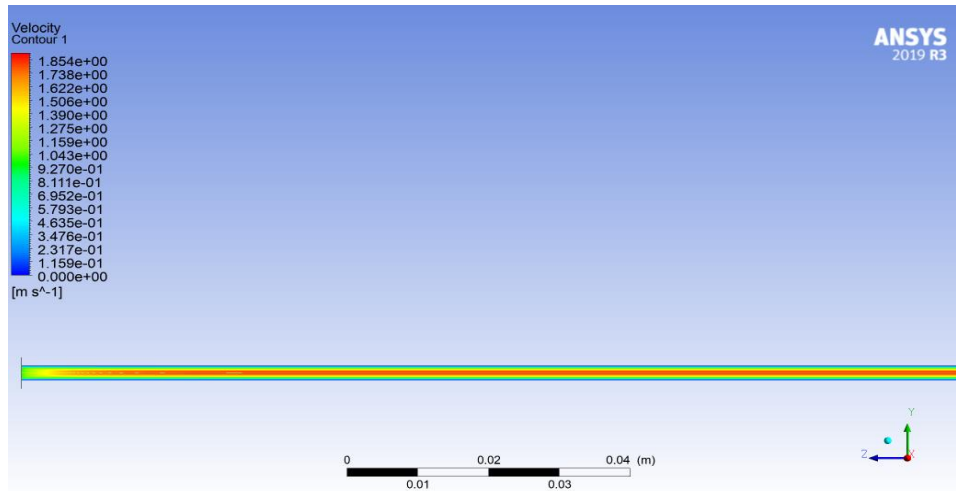


Figure 6: Velocity Contour Plot for Smooth Pipe

The rough pipe on the other hand did not have a fully developed flow, and this is linked to the roughness of the pipe inner surface. The velocity profile of the graph is plotted (fig 7) and the contour plot is also obtained (fig 8).

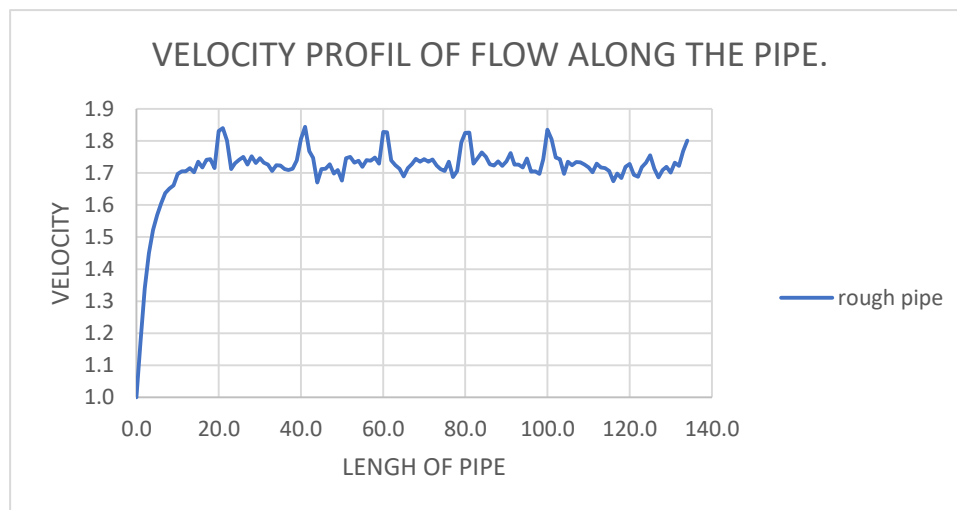


Figure 7: Velocity Profile for Rough Pipe

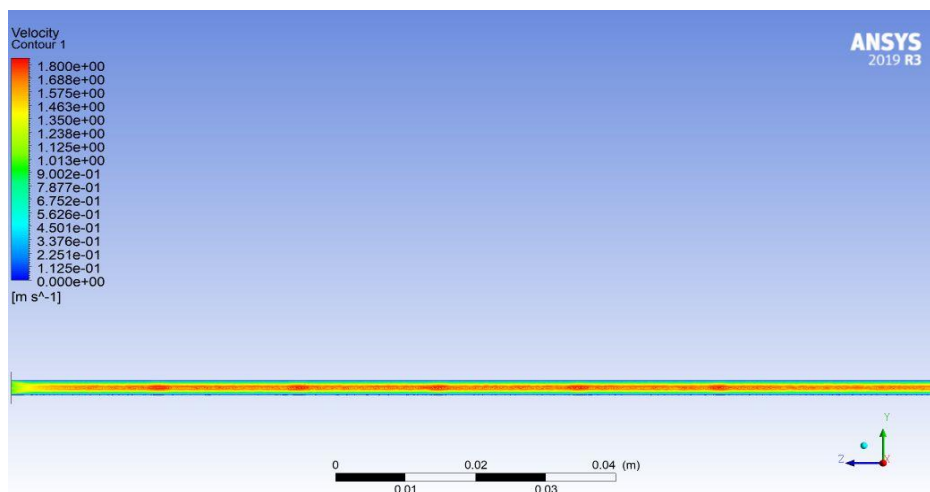


Figure 8: Velocity Contour Plot for Rough Pipe

FLUID FLOW CHARACTERISTICS

The pressure drop along the pipe was calculated in both cases; the smooth pipe and the rough pipe. A roughness size of 1micron was used and the variation of pressure drop with change in the surface roughness was observed. The results of both cases are shown in table 2

Table 2: Pressure Drop

Surface Condition	Pressure drop (Pa)
Smooth	7377.6817
Rough (1 micron)	7697.9812

From the table it is clear that there is a higher pressure drop in the rough pipe than in the smooth pipe. This result aligns with the studies found in literature [1][2]. The pressure along the two pipes are then plotted on the same graph for comparison as shown in figure 9

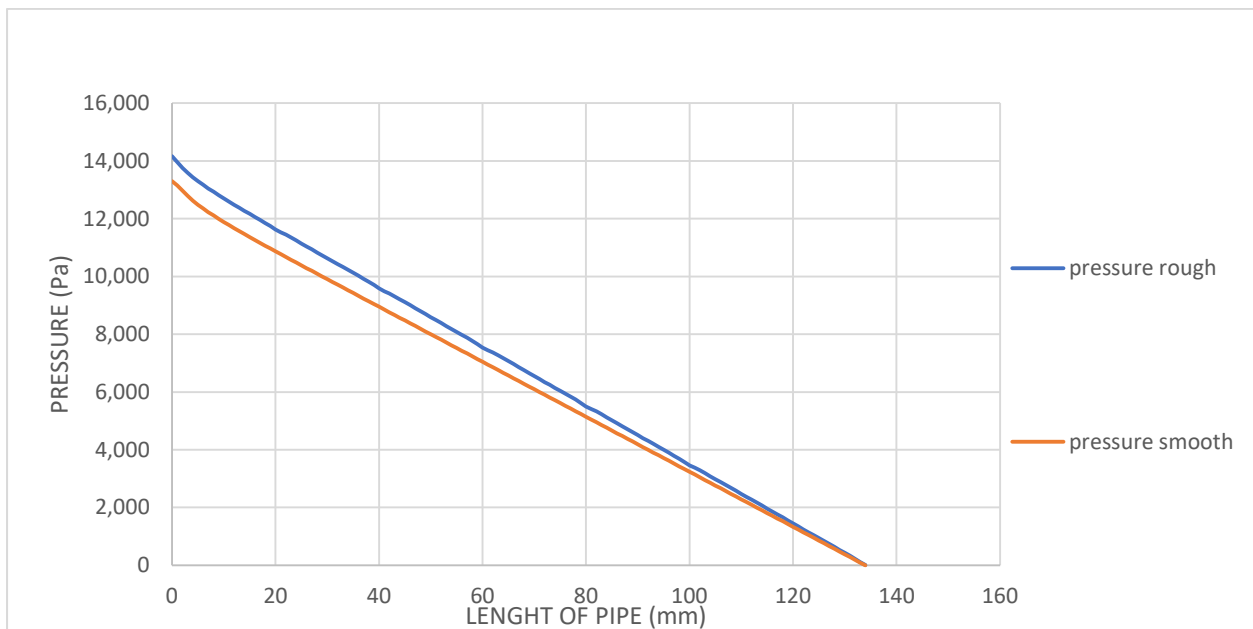


Figure 9: Pressure Drop along the Two Pipes

Clearly, from the graph the slope of the plot for rough surface is higher than that for the smooth surface. At every point on the graph, a change in the pressure for the rough surface will be higher than the corresponding smooth surface. Hence, this further confirms the effect of surface roughness on the pressure drop in the pipe.

The size of the roughness on the pipe is then varied to check for effect of increase in the roughness size on the pressure drop in the pipe. Several sizes were considered and the corresponding pressure drop were obtained. The result is shown in table 3

Table 3: Pressure Drop for Different Roughness Size

Roughness size (µm)	Pressure drop (pa)
1	9862.864
5	9838.98
10	10063.73
50	10085.64
100	10651.56
200	10710

V. CONCLUSION

The effect of inner surface roughness on pressure drop in small diameter pipe has been determined in this work using the ANSYS FLUENT software. The analysis was carried out for both a smooth pipe and a rough pipe. The CFD results showed a higher pressure drop in the rough pipe than the smooth pipe, and this is in correlation with already published works.

The size of the roughness on the pipe wall was then increased to check the effect of increase in size on the pressure drop in the fluid flow. The result also showed that an increase in roughness size correspond to an increase in pressure drop albeit not proportional.

Hence, the effect of inner surface roughness on the pressure drop in a small pipe shows it increases the pressure drop in the pipe.

REFERENCES

- [1] Liu Y, Li J, Smits AJ. Roughness effects in laminar channel flow. *J Fluid Mech.* 2019;876:1129–45.
- [2] Kandlikar SG, Joshi S, Tian S. Effect of surface roughness on heat transfer and fluid flow characteristics at low Reynolds numbers in small diameter tubes. *Heat Transf Eng.* 2003;
- [3] Yuan X, Tao Z, Li H, Tian Y. Experimental investigation of surface roughness effects on flow behavior and heat transfer characteristics for circular microchannels. *Chinese J Aeronaut.* 2016;29(6):1575–81.
- [4] Peng XF, Peterson GP. Convective heat transfer and flow friction for water flow in microchannel structures. *Int J Heat Mass Transf.* 1996;
- [5] Mohiuddin Mala G, Li D. Flow characteristics of water in microtubes. *Int J Heat Fluid Flow.* 1999;
- [6] Yang CY, Lin TY. Heat transfer characteristics of water flow in microtubes. *Exp Therm Fluid Sci.* 2007;
- [7] Zhao Q, Yue X, Wang F. Gas flow property in microtube and its effect on gaseous seepage. *Pet Sci Technol.* 2014;
- [8] Hasan MI, Hasan HM, Abid GA. Study of the axial heat conduction in parallel flow microchannel heat exchanger. *J King Saud Univ - Eng Sci.* 2014;
- [9] Ibrahim MB, Veluri S, Simon T, Gedeon D. CFD modeling of surface roughness in laminar flow. *Collect Tech Pap - 2nd Int Energy Convers Eng Conf.* 2004;1(August):556–63.
- [10] Farshad F, Rieke H, Garber J. New developments in surface roughness measurements , characterization , and modeling fluid flow in pipe. 2001;139–50.
- [11] Asme B. SURFACE TEXTURE (SURFACE ROUGHNESS , WAVINESS , AND LAY). 2002;2002:1–5.
- [12] Kandlikar SG, Schmitt D, Carrano AL, Taylor JB. Characterization of surface roughness effects on pressure drop in single-phase flow in minichannels. *Phys Fluids.* 2005;17(10).