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AVERAGE SUPERFICIAL ROUGHNESS ANALYSIS OF MANUFACTURED PIPES BY 3D PRINTING

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Abstract. *The fast development of prototyping technologies allowed the optimization of engineering projects in several areas. On this paper was used methods to achieve an absolute value for the average superficial roughness parameter in pipes manufactured in different 3D printers. The study is divided in two phases: first, testing three rectangular samples to determine the surface roughness value with a roughness meter, produced by a FDM printer VOID3D 1+ model. Second, the superficial roughness was defined by a friction head loss test done on a hydraulic bench with the conducts manufactured by the same material mentioned previously with different layer heights for them, which has influence on the average superficial roughness calculated. The results reached showed that although the found values have great discrepancy, the decreasing tendency presented between the friction factor (f) and Reynolds number (Re) was kept, following the Moody's diagram leaning curves. In addition, the same proportion from the first experiment was sustained, when it was possible to see that the higher layer height has the lowest average superficial roughness and the lower layer height has the higher superficial roughness.*

Keywords: *Surface Roughness, Friction Head Loss, ABS Plastic, 3D Printing.*

1. INTRODUCTION

Incompressible fluids internal flow in ducts corresponds to a well-known area of knowledge in engineering since its applied on the most varied segments, which makes it an important area of study in order to have a greater control of the phenomena involved.

The fluid viscosity, the resistance offered by the surface of the conduct and its roughness imply directly on internal flow of the pipeline. These parameters are responsible for some pressure dropping as the flow is developing and it can be defined as friction head loss, which according to Çengel (2012) is caused by the viscous effects and is directly related to the shear stress between the conduct wall and the fluid.

Frictional head loss can be divided in two: major losses, which occur along the pipe network and have higher values; minor losses, that are additional losses due to separation of the flow when passing through components that interrupt the smooth flow of the fluid.

Any material surface, even those with better finishing, have irregularities that can come from the material itself, or from marks left by the tools which acted on the part's surface during its manufacture. These irregularities are called roughness, measured with a roughness meter, or by alternative methods applications.

According to Hutchings (1992), it is the roughness that influence the sliding capacity, wear resistance, coupling fit, resistance to fluid and lubricant flow, adhesion quality to protective layers, corrosion resistance and fatigue, in the seal and appearance of the materials.

The most widely used method for measuring surface roughness is the M-line, adopted in countries such as Brazil, England, Japan, the United States of America and Russia. This procedure consists in defining all the quantities from a reference line (midline) that is parallel to the general direction of the profile, in the sampling length. In Brazil, the M-line system has its parameters defined by the ABNT 4287 (2002) standard.

Arithmetic mean height, or just average roughness, is mathematically defined as the arithmetic mean of the absolute values from the spacing ordinates of roughness profile points in relation to the midline within the measurement path. This is the most used parameter to determine the surface roughness, since it is applicable to most manufacturing processes and the risks inherent in the processes, they change their value little.

This work aims to compare the internal surfaces roughness of pipes manufactured from different methods of 3D printing. This parameter first were determined by a rugosimeter test and then was defined analytically by experiments performed on a hydraulic bench, where finally both results were compared. The experiments were performed, respectively, in the Metrology Lab and the Fluid Mechanics Lab from the Universidade Federal do Rio Grande do Norte (UFRN).

In 3D printing the model to be printed is sliced in several transversals planes along an axis like one. The number of layers along the axis is defined by the ratio between the object height to be printed and the layer height defined at printing time, as it is shown at Fig. 1 . The visible surface quality and the printing time are inversely proportional to the layer height.

Fusion Deposition Modeling (FDM) is an additive manufacturing process which objects are built by depositing melted thermoplastic in a pre-determined path, layer-by-layer, and according to Dudek (2013) it is the most common 3D printing technique.

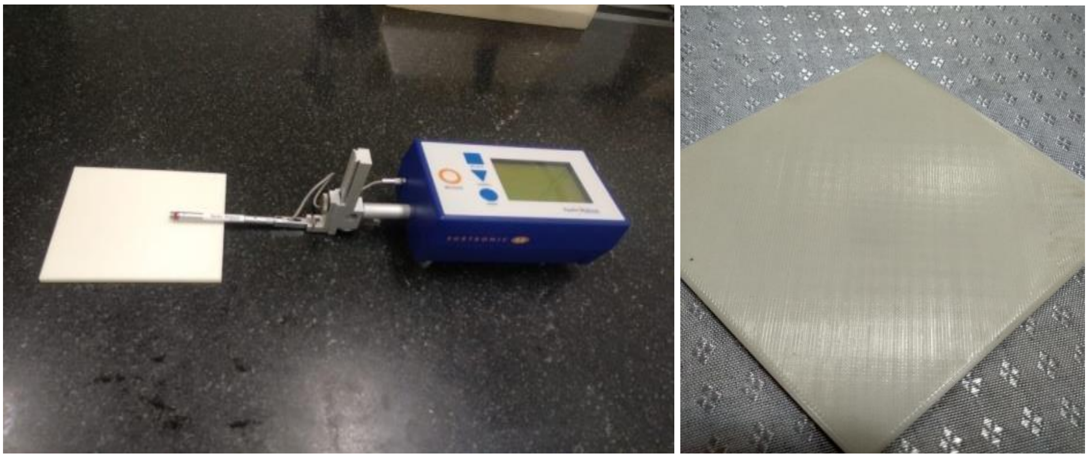
Figure 1. Slices and FDM printing example.
Available from: https://shropshire3dprinters.co.uk/media/wysiwyg/i.png

2. METHODOLOGY

For roughness analysis was determined two values of average roughness for each material: one coming from the first experiment, with a roughness meter, and another from the second experiment, on the hydraulic bench. The arithmetic mean between the obtained values is calculated in order to define an absolute value for the parameter adopted to this study.

The first experiment was done with a Taylor Hobson Surtronic 25 roughness tester, calibrated, with its probe performing a 4 mm as the sampling length, perpendicular and parallel to the printing direction (three times for which orientation) because the layer heights in different directions can make difference on the fluid flow resistance and cause directly influence on the pressure drop. It is worthwhile to mention that 0.8 mm referents to the initial and the final path of the sampling is discarded to allow the mechanical and electrical oscillations of the measuring system to be damped, and following the definition given by Hutchings (1992) the sampling length divide by 5, gives the cut-off value equal to 0.8 mm.

Three rectangular samples were used on the experiments, produced by FDM with ABS plastic (Stratasys, 2019), in a VOID3D 1+ printer, measuring 100 mm x 100 mm each, with 0.1, 0.2 and 0.3 mm layer height; The Fig. 2a refers to the procedures described previously.

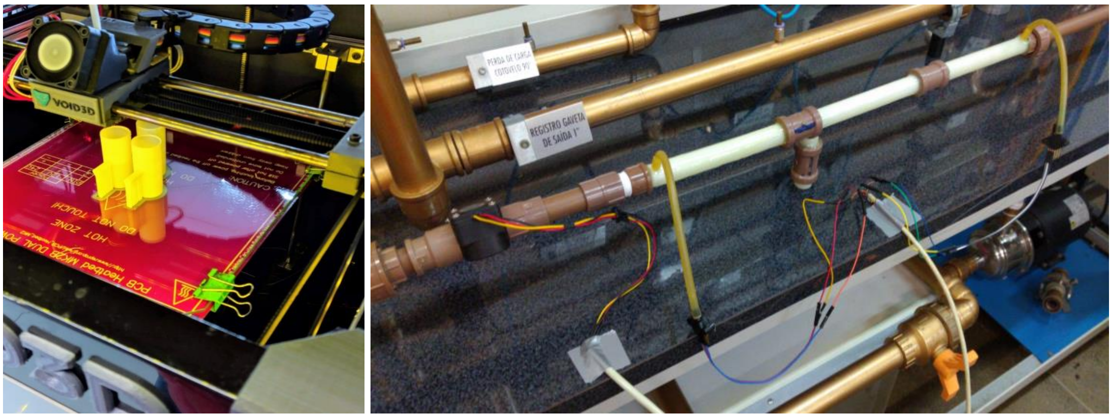


(a) (b)

Figure 2. (a) Average roughness measurement, perpendicular to the printing direction; (b) 0.3 mm layer height sample in details, to check the direction of the filament deposited during the printing.

To print the ABS plastic samples it was set 230 ºC for the hot end temperature, 110 ºC for the table temperature, the printing direction was inside-out, the infill type as the fast honeycomb, with 30% of infill, the printing speed as 4800 mm/min and the printer resolution is 0.15 mm.

The second experiment is to determine the average superficial roughness value through head loss test done on a hydraulic bench. The results to be achieved should consider the printing direction on the pipes' internal surface and the different layer heights, so that they are compared with the equivalent values on the first experiment.



(a) (b)

Figure 3. (a) Tubes being printed; (b) Pipes network installed on the hydraulic bench.

On the hydraulic bench built for the experiment it was used a peripheral water pump from WEG with 735.5 Watts of power. The sampling length has 0.55 m formed by three tubes with 0.2 m long each (Fig. 3b), 1.5 mm of wall thickness and 18.5 mm of internal diameter, produced by the FDM printer described previously to obtain an average roughness values and reach a calculated absolute value, which will be compare with found results before for the same materials.

Inside the conducts it will flow water at 25 ºC, with 8.93×10^{-4} [(N · s)/m^2] for dynamic viscosity (μ), 8.96×10^{-7} (m^2/s) for kinematic viscosity (ν) and 997 (kg/m^3) for density (ρ). After the tubes were manufactured, it was verified that there is no change of the tubes diameter over the path and because the bench has no height variation, it means that there is no change on the velocity flow and potential energy of the system from the inlet to the outlet. Also, it does not have any components that will interrupt the smooth flow of the fluid, then there are no minor losses values.

Therefore, it has the Eq. (1) with the friction factor (f), $P1$ and $P2$ which are the measured pressures on the transducers, the internal diameter of the tube (D), the gravity (g), the water's specific weight (γ), the flow's velocity (V), and the pipes length (L).

$$f = \frac{(P1 - P2) * D * 2g}{L * V^2 * \gamma} \tag{1}$$

The pressures in the pipes network was measured at the inlet (P1) and outlet (P2) in Pascal (Fig. 4a), using a MPX5050DP differential pressure sensor which gauges the analog signal to pass through a RC LP filter hardware system to filter out noise, formed by capacitors of 0.01 µF, 0.33 µF and 1.00 µF and a resistor of 150 Ω, as the electric circuit presented on Fig. 4b. All this electronic scheme described is a low cost data acquisition system, which was assembled using an ESP32 chip microcontroller, implemented using the Arduino IDE software and a ADS1115 card to convert the analog signal to a digital signal with 16 bit's resolution. The flow rate (Q) is also collected (in m³/s) by a microcontroller which is the Arduino Nano.

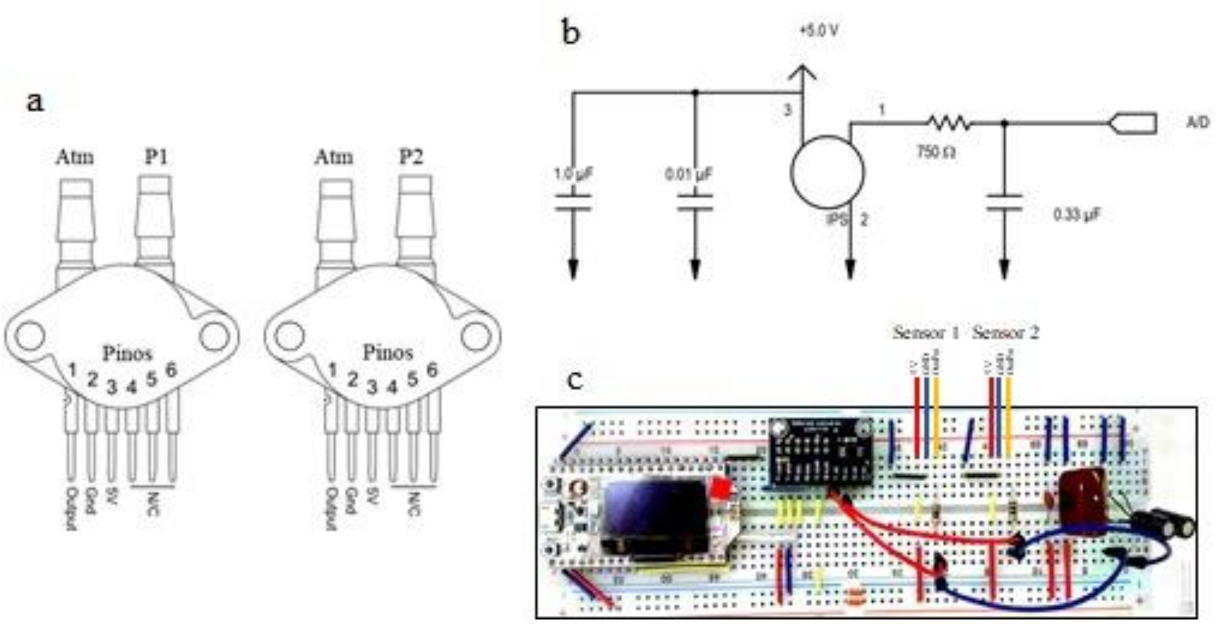


Figure 4. Low cost data acquisition system built by the authors.

With all values known and also with the water properties values, it is possible to calculate the friction factor (f) and the Reynolds number, for that flow. Knowing that values and the conducts' internal diameter, it will be applied the Eq. (2), which was reported by Fox (2012) as alternative way to avoid the need to use graphical methods to obtain the friction factor (f) in turbulent flows. Several mathematical expressions were created by adjusting experimental data, being the most common the Colebrook - White equation.

The Eq. (3) it is the manipulation of the Eq. (2) to obtain the relative pipe roughness. As the internal diameter is known, it is finally achievable to reach the absolute pipe's superficial roughness.

Another way to reach the relative roughness is using the Moody diagram, see LaViolette (2017).

$$\frac{1}{(f)^{0.5}} = -2\log\left(\frac{\varepsilon}{3.7D}\right) + \frac{2.51}{Re*(f)^{0.5}} \tag{2}$$

$$\frac{\varepsilon}{D} = 3.7\left[10^{\left(\frac{1}{-2*(f)^{0.5}}\right)} - \frac{2.51}{Re*(f)^{0.5}}\right] \tag{3}$$

$$Re = \frac{\upsilon * D * V}{\mu} \tag{4}$$

All calculations must consider the gravity as 9.81 m/s.

3. RESULTS AND DISCUSSION

The Tab.1 shows the average roughness values measured and the arithmetic mean of them for each layer height, the measurement direction and the standard deviation to verify the homogeneity of the collected data.

Table 1. Average roughness results for the plates made of ABS plastic and the arithmetic mean calculated for each layer height.

Layer Height: 0.1 mm					
	Average Superficial Roughness (μm)			Arithmetic Mean (μm)	Standard Deviation (μm)
Parallel to the Printing Direction	3.80	3.40	3.20	3.46	0.31
Perpendicular to the Printing Direction	13.40	13.00	13.80	13.40	0.40
Layer Height: 0.2 mm					
	Average Superficial Roughness (μm)			Arithmetic Mean (μm)	Standard Deviation (μm)
Parallel to the Printing Direction	0.80	1.40	1.20	1.13	0.31
Perpendicular to the Printing Direction	10.20	10.40	10.20	10.26	0.12
Layer Height: 0.3 mm					
	Average Superficial Roughness (μm)			Arithmetic Mean (μm)	Standard Deviation (μm)
Parallel to the Printing Direction	0.80	1.80	0.80	1.13	0.58
Perpendicular to the Printing Direction	6.00	7.40	6.20	6.53	0.76

It can be observed that the analyzes made with the roughness tester probe sweeping the ABS plastic samples in the parallel way of printing direction found values much smaller of average roughness than when the experiment was made on the perpendicular way of printing direction. These results are reflected on the large difference between the absolutes values of the arithmetic mean. However, the results for the parallel printing direction will be not considered because they are not representative as the values for the other direction and, according to Leach (2014), after take measurements in different directions, it must be consider the highest roughness value indicated as the correct value.

In addition, it was not possible to print the tubes with grooves parallel to the flow because the FDM printer could not form the pipe wall (see Fig. 5) and thus, the head loss analysis was not made for these samples, making it impossible to compare them with the results obtained with the roughness tester.

Figure 5. Attempt to print the tubes with grooves parallel to the flow in the FDM printer.

On Tab. 2 it is shown the difference between the pressures measured during the experiment on the hydraulic bench, the flow rates acquired, the calculated Reynolds number (Re) by Eq. (4) and the friction factor, and the standard deviation to verify the homogeneity of the collected data.

Table 2. Pressure drops, flow rates, Reynolds numbers and friction factors gauged on the hydraulic bench test and calculated for each layer height for the pipes network made of ABS plastic.

Layer Height: 0.1 mm				Layer Height: 0.2 mm				Layer Height: 0.3 mm			
P1-P2 (Pa)	Q (m^3/s) $x10^{-4}$	Re $x10^4$	f	P1-P2 (Pa)	Q (m^3/s) $x10^{-4}$	Re $x10^4$	f	P1-P2 (Pa)	Q (m^3/s) $x10^{-4}$	Re $x10^4$	f
1060	2.39	1.84	0.09	360	1.71	1.32	0.06	150	2.12	1.63	0.02
2370	2.67	2.00	0.16	460	1.91	1.47	0.06	420	2.47	1.90	0.03
4860	2.97	2.28	0.27	600	2.19	1.68	0.06	340	2.61	2.01	0.02
3100	3.24	2.50	0.14	900	2.27	1.74	0.09	290	2.77	2.13	0.02
3780	3.38	2.60	0.16	730	2.48	1.90	0.06	710	2.91	2.24	0.04
3930	3.52	2.70	0.16	900	2.54	1.95	0.07	930	3.07	2.36	0.05
3780	3.72	2.86	0.13	790	2.62	2.01	0.06	600	3.26	2.51	0.03
3700	3.88	2.98	0.12	1150	2.97	2.28	0.06	430	3.40	2.61	0.02
3540	4.21	3.24	0.10	1060	3.13	2.40	0.05	220	3.47	2.67	0.01
3300	4.29	3.30	0.09	1240	3.26	2.50	0.06	460	3.04	2.33	0.02
3280	4.40	3.38	0.08	1070	3.40	2.61	0.05	130	3.38	2.59	0.01
3100	4.53	3.48	0.07	810	3.51	2.70	0.03	270	2.91	2.24	0.02
3250	4.67	3.59	0.07	1110	2.92	2.24	0.06	910	2.47	1.90	0.07
Standard Deviation											
-	0.00	-	-	0.00	-	-	0.00	-	0.00	0.00	-

The tables data above shows that while the pressure differential is increasing, the flow rate is also growing and consequently the fluid velocity is rising, which makes the Reynolds number enhance and the friction factor decline, simultaneously. The behavior described repeats for all layer heights tested. The friction factor decrease and the Reynolds number rising are expressed in the following graph.

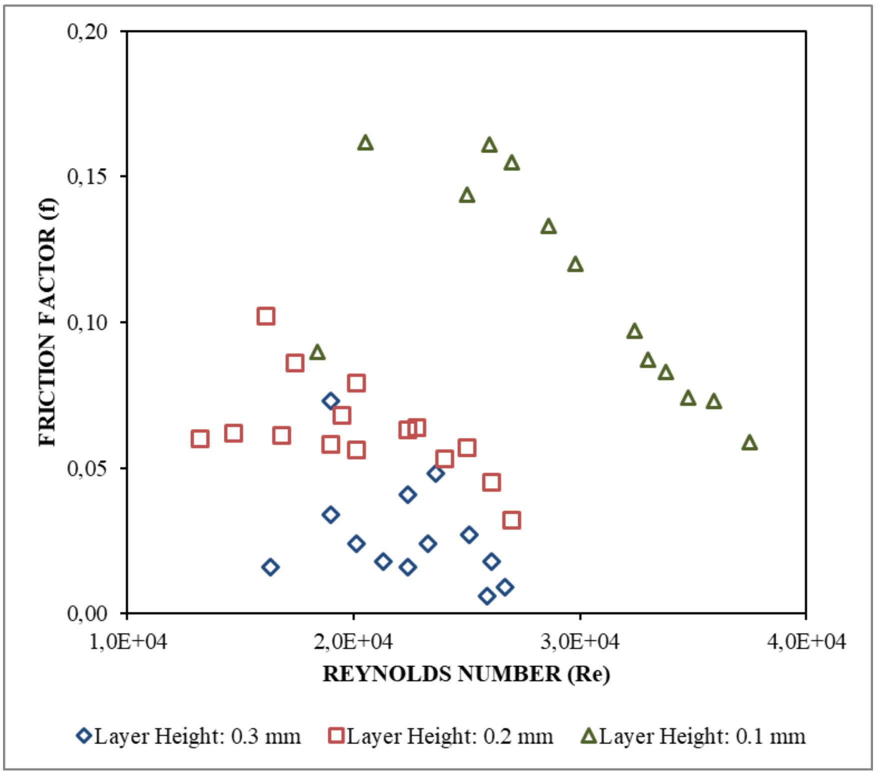


Figure 6. Friction factor decreasing tendency with the Reynolds numbers rising.

It can be noticed that the intersection points for the Reynolds numbers and the friction factors present the formation of a decreasing curve, exactly as in the previous table. According to the layer heights one can observes that for this Reynolds number range, the friction factor has a fall on its value while the layer height is growing.

Therefore, it is worth to mention that the points where the friction factor and the Reynolds number are coincident, on the Moody diagram, represents the relative roughness which keeps the same behavior presented on the first experiment when it was possible to see that the higher layer height has the lowest average superficial roughness and the lower layer height has the higher average superficial roughness.

As described in the previous section, the relative roughness was calculated by the Eq. (3) and then multiplied by the internal diameter to be equal to the superficial roughness.

Table 3. Relative roughness and absolute roughness calculated with the Reynolds numbers and friction factors by hydraulic bench test for each layer height's pipes network made of ABS plastic.

Layer Height: 0.1 mm				Layer Height: 0.2 mm				Layer Height: 0.3 mm			
Re $x10^4$	f	Ɛ/D	Ɛ (μm) $x10^3$	Re $x10^4$	f	Ɛ/D	Ɛ (μm) $x10^3$	Re $x10^4$	f	Ɛ/D	Ɛ (μm) $x10^3$
1.84	0.09	0.08	1.44	1.32	0.06	0.03	0.57	1.63	0.02	0.00	-0.07
2.05	0.16	0.21	3.90	1.47	0.06	0.03	0.62	1.90	0.03	0.00	0.08
2.28	0.27	0.40	7.42	1.68	0.06	0.03	0.60	2.01	0.02	0.00	-0.01
2.50	0.14	0.18	3.28	1.74	0.09	0.07	1.32	2.13	0.02	0.00	-0.04
2.60	0.16	0.21	3.87	1.90	0.06	0.03	0.53	2.24	0.04	0.01	0.19
2.70	0.16	0.20	3.66	1.95	0.07	0.04	0.79	2.36	0.05	0.02	0.32
2.86	0.13	0.16	2.90	2.01	0.06	0.03	0.49	2.51	0.03	0.00	0.02
2.98	0.12	0.13	2.45	2.28	0.06	0.04	0.69	2.61	0.02	0.00	-0.03
3.24	0.10	0.09	1.68	2.40	0.05	0.02	0.43	2.67	0.01	0.00	-0.06
3.30	0.09	0.07	1.36	2.50	0.06	0.03	0.52	2.33	0.02	0.00	-0.00
3.38	0.08	0.07	1.24	2.61	0.05	0.01	0.27	2.59	0.01	0.00	-0.08
3.48	0.07	0.05	0.97	2.70	0.03	0.00	0.07	2.24	0.02	0.00	-0.05
3.59	0.07	0.05	0.95	2.24	0.06	0.04	0.66	1.90	0.07	0.05	0.93
Standard Deviation											
-	0.05	0.10	-	-	0.01	0.02	-	-	0.02	0.02	-

On Tab. 3 it is presented the values for the average superficial roughness for each flow situation and layer height and it can be noticed that the values decrease while the layer height is rising.

The highest absolute values found for the superficial roughness was on the samples with the lowest layer height (0.1mm), probably because at the same sampling length occurs more undulating - three times more than on the 0.3 mm layer height. This big difference between the values found on both experiments maybe occurs by the methods applied to take pressures, which has the pipes fittings too close where it was measured and could have an minor loss associated, and also the printer inaccuracy to guarantee the same roughness on all the pipe's length generated for the own printer's vibration.

4. CONCLUSION

After the experiments described in this paper are done and all the data needed were collected and analyzed, it is possible to conclude that although the values found for the average superficial roughness when are compared have a great discrepancy, the decreasing tendency, as the Moody's diagram curves, followed by the presented behavior between friction factor and Reynolds number and the kept proportion among higher layer height to lowest superficial roughness and lower layer height to higher superficial roughness absolute values makes this study relevant.

The methods applied to gauge the pressures and the inaccuracy generated for the printer vibration, should be the motivations of the big difference of the average superficial roughness value found because the pipes fittings maybe be too close to where it was measured the pressures and might have a minor friction head loss associated not considered, and also by printer not ensure the same roughness on all the pipe's length.

In addition, the results of this study were evaluated as satisfactory because although the mean surface roughness values did not coincide in both experiments, the peer-to-peer analysis of the relative roughness ratio, which is dependent on the friction factor and the Reynolds number, showed a similar tendency to Moody's diagram curves.

Therefore, to define material roughness evaluated on this paper, considering the layer heights on each sample, contributes with the developing studies at Fluid Mechanics Laboratory, from the Federal University of Rio Grande do Norte, which will compare the ideal flow in a arteriovenous fistula (AVF) with a 3D printed model on a benching test, where it will simulate the real flow. For this, it is necessary to know all the associated variables to characterize the flow along a specific length and to calculate the friction head loss, where it must have the roughness.

5. ACKNOWLEDGEMENTS

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