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Experimental Analysis of the Explicit Approximation of the Colebrooks Equation

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Abstract: The well-known equation of Colebrook-White is defined as a relationship between the friction factor and the Reynolds number, pipe roughness, and inside diameter of pipe. It is widely used to calculate friction factor in pipes with accepted accuracy over a wide range of Reynolds number and relative roughness. Considering that Re and λ are dimensionless and having consistency with the roughness (ε) and diameter (D) units, the equation is the same. The disadvantage of this equation is that it has not an explicit form. The friction factor must be calculated using a trial-and-error approach as it appears on both sides of the equation. Different authors have established a reasonable approach for Colebrook-White equation but which the friction factor is explicit. The reason lies on fact that iterative calculation could cause problems in simulation of pipe flow leading to evaluate the friction factor many times. The present work shows the results of friction factor for a given Reynolds and pipe roughness obtained by applying different approximations for Colebrook-White equation. Also, these results are compared with experimental data extracted through a test section of 14 meters of pipe where roughness, inside diameter and Reynolds were known. Finally, it can be concluded the relative error for each approximation and their range of applicability.
Keywords: Colebrook-White equation, friction coefficient, Darcy friction factor, Moody Diagram, Turbulent flow

I. INTRODUCTION

The fluid mechanics has several fields of study which includes one of a greater importance called the flow of fluids trough conduits. This topic is widely spread and could be found anywhere from the blood flowing through a human vain or the oil passing inside a steel pipe. With the flow, also comes a lot of questions such as the value of the friction factor along a pipe.

The friction factor is a valuable parameter that permits engineers to find the pressure loss through a pipe.

A variety of equations have been developed throughout the years to find this value given certain conditions of Reynolds, pipe roughness and diameter.

A recognized equation called the Colebrook-White equation was developed by Colebrook and White in 1937 based on experimental data with the flow of air through a set of pipes which roughness were created artificially by sand grains. Unfortunately, this equation assumes an implicit form. The Colebrook-White function relates the unknown flow friction factor λ as function of itself, the Reynolds number Re, and the relative roughness of inner pipe surface ε/D. It is applicable for $4000 < Re < 10^8$ and for $0 < \varepsilon/D < 0.05$. Because this equation is transcendent and cannot be solved in terms of elementary functions many authors have developed approximations for the value of the friction factor.

One of the most recognized approximation of this value is the Moody Diagram which is a graphical resolution for the friction factor. This diagram was developed by Rouse in 1942, and later adapted in 1944 by Moody. Nowadays this graphical solution has only value for learning purposes.

This work analyses different explicit equations for a value of roughness and Reynolds. The roughness was obtained through experimental data. The experiment consisted of water flowing through a stainless-steel pipe with 14 meters of length. Also, the relative error between the experimental data and Colebrook approximations were calculated. Different graphs of head loss versus length were plotted to show how much the approximations deviate from the experimental data.

II. THE COLEBROOK EQUATION AND ITS APPROXIMATIONS FOR CALCULATION OF THE FRICTION FACTOR IN TURBULENT FLOW

The pressure drop in pipelines is an extremely important parameter in the design of any hydraulic system and is influenced by the flow resistance. According to Coban (2012), the Colebrook-White equation is an implicit formula that generates the best result for the pressure loss coefficient in turbulent regime; however, it does not have a trivial solution. Several authors have presented explicit equations to the friction factor which has a simpler solution; however, coherent and applicable.

A. Colebrook-White equation
The Colebrook-White equation has been considered the most accurate approximation for the Darcy-Weisbach friction factor. It is the result of the experiments carried out by Colebrook and White in 1937 where they concluded that adding the argument of the logarithm function of the Prandtl-Von Kármán to the argument logarithm of the formula function of Von Kármán the expression below was obtained.

$$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{\mathrm{Re}\sqrt{\lambda}}\right) \tag{1}$$

B. Moody Approach
The approach proposed by Moody (1974) is the oldest approach to the Colebrook-White implicit equation. It was developed based on the Hagen-Poiseuille and Colebrook-White formulas where it was possible to explicitly calculate the friction factor as a function of the Reynolds number and relative roughness without using iterative solutions.

$$\lambda = 0.0055\left[1 + \left(2x10^{4}\frac{\varepsilon}{D} + \frac{10^{6}}{\mathrm{Re}}\right)^{\frac{1}{3}}\right] \tag{2}$$

C. Wood Approach
Wood's (1966) approximation is similar to that proposed by Moody (1947), as both are power law equations; however, this correlation is only valid for regions where $\mathrm{Re} > 10^{4}$ and $10^{5} < (\varepsilon / D) < 4x10^{-2}$.

$$\lambda = a + b * \mathrm{Re}^{-c} \tag{4}$$

Where:

$$a = 0.53\left(\frac{\varepsilon}{D}\right) + 0.094\left(\frac{\varepsilon}{D}\right)^{0,225} \tag{5}$$

$$b = 88\left(\frac{\varepsilon}{D}\right)^{0.44} \tag{6}$$

$$c = 1.62\left(\frac{\varepsilon}{D}\right)^{0,134} \tag{7}$$

D. Churchill Approach
According to Churchill (1977) this equation was developed from theoretical and correlative equations for the laminar flow, transition and fully developed regimes, using a general model created by Churchill and Usagi.

$$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{\varepsilon}{3.71D} + \left(\frac{7}{\mathrm{Re}}\right)^{0.9}\right) \tag{8}$$

E. Eck Approach
The approximation model proposed by Eck (1973) does not have a recommended interval where the equation is applicable.

$$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{\varepsilon}{3.71D} + \frac{15}{\mathrm{Re}}\right) \tag{9}$$

F. Haaland Approach
Haaland (1983) proposed a model based on a combining of the approximation of the Prandtl formula for smooth tubes with Von Kàrmàn's formula for rough tubes, which resulted in the equation below.

$$\frac{1}{\sqrt{\lambda}} = -1.8\log\left[\left(\frac{\varepsilon}{3.7D}\right)^{1.11} + \frac{6.9}{\mathrm{Re}}\right] \tag{10}$$

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G. Tsal Approach

Tsal (1989) proposed the model is show in the Eq. (xx). This model is valid for intervals where $4x10^3 < \mathrm{Re} < 4x10^8$ and $0 \le (\varepsilon / D) \le 5x10^{-2}$.

$$A = 0.11\left(\frac{68}{\mathrm{Re}} + \frac{\varepsilon}{D}\right)^{0.25} \tag{11}$$

Where:

$$A \ge 0.018; \lambda = A \tag{12}$$

$$A < 0.018; \lambda = 0.0028 + 0.85A \tag{13}$$

H. Buzzelli Approach

Buzzelli model (2008) is based in 69 numbers chosen randomly for Reynolds number where $2300 \le \mathrm{Re} \le 10^8$ and (ε / D) between 0 (smooth) to 0.05 (rough).

$$\frac{1}{\sqrt{\lambda}} = A - \left[\frac{A + 2\log\left(\frac{B}{\mathrm{Re}}\right)}{1 + \left(\frac{2.18}{B}\right)}\right] \tag{14}$$

Where A and B are expressed by the following equations (15) and (16)

$$A = \frac{(0.744\ln(\mathrm{Re}) - 1.14)}{\left(1 + 1.32\sqrt{\frac{\varepsilon}{D}}\right)} \tag{15}$$

$$B = \frac{\varepsilon}{D}\mathrm{Re} + 2.51A \tag{16}$$

I. Altshul Approach

The model proposed by Altshul (1952) provides the basis for Tsal's model (1989), although it does not have the correction factors that is proposed by Tsal's model (1989).

$$\lambda = 0{,}11\left(\frac{68}{\mathrm{Re}} + \varepsilon\right)^{0{,}25} \tag{17}$$

J. Round Approach

The correlation presented by Round (1980) is valid for $4x10^3 < \mathrm{Re} < 4x10^8$ e $0 < \varepsilon < 0.05$. This model modifies the one proposed by Altshul which is based on Konakov models (1968).

$$\lambda = -1{,}8\log\left(0{,}135\varepsilon + \frac{6{,}5}{\mathrm{Re}}\right) \tag{18}$$

III. EXPERIMENTAL DATA

This article presents a comparison between the friction factors obtained when applying the different Colebrook-White approximations and the experimental data obtained in the work of Bandeira (2015). Bandeira performed an experimental analysis to find the head loss in a rough pipe. The results revealed an excellent cohesion when compared with Colebrook-White equation. This work presents an analysis based on the data from Bandeira and which are shown in Table 1. Each experimental data from Table 1 represents the best estimate of each measurement or the mean value.

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TABLE I
Experimental data

Experimental Data	Values
Volumetric flow (m^3/h)	3.31
Velocity (m/s)	1.16
Roughness (m)	0.000179
Density (kg/m^3)	997.00
Pipe diameter (m)	0.03175
Length (m)	14.00

The experimental data obtained from Bandeira (2015) and used in this article are 3.31 m^3/h of water flowing inside a stainless-steel pipe of 14 meters length. Figure 1 shows the test section used to obtain the data used in this work.

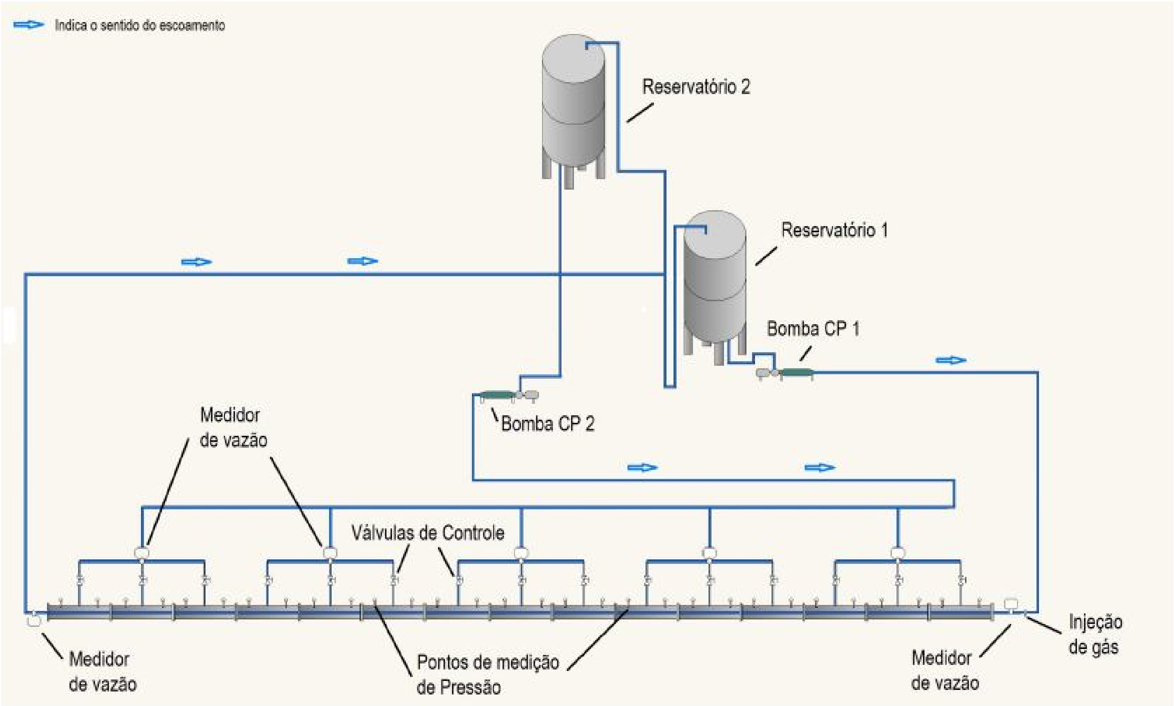

Fig. 1 Test section used by Bandeira (2015)

IV. ANALYSIS OF RELATIVE ERROR

According to Asker et al (2014), the calculation that will be the basis for the analysis of the approximations in relation to the Colebrook-White equation will be that of the relative error. As per equation (19), the relative error shows how close the result of the coefficient of the explicit equation will be when compared to the coefficient

$$\Psi = \left[\frac{(f_{colebrook} - f_{\mathrm{mod}})}{f_{colebrook}} \right] \times 100 \tag{19}$$

To determine the relative error in relation to the experimental data, equation (20) was used:

$$\Psi = \left[\frac{(f_{\exp} - f_{\mathrm{mod}})}{f_{\exp}} \right] \times 100 \tag{20}$$

Table II contains the relative error when equation (19) and (20) was applied

TABLE III
friction factor values when applying different models

Model	Friction factor	error Colebrook (%)	error exp (%)
Tsal	0.03235	4.000	4.164
Haaland	0.03362	0.232	0.402
Colebrook – White	0.03370	0.000	0.170
Buzelli	0.03373	-0.087	0.083
Bandeira (experimental)	0.03376	-0.170	0.000
Eck	0.03391	-0.622	-0.451
Moody	0.03376	-1.04	-0.868
Wood	0.03405	-1.246	-1.074
Churchill	0.03414	-1.294	-1.122
Altshul	0.03235	4.012	1.181
Round	0.03366	0.1255	-2.821

V. RESULTS AND DISCUSSION

The Colebrook-White equation is used to accurately determine the friction factor; however, its form is implicit and require a numerical solution. Authors such as Moody (1974), Woody (1966), Eck (1973), generated mathematical models with approximate solutions to the Colebrook-White equation. All of them are subject to errors, which depending on the roughness conditions, Reynolds number and viscosity, can present significant errors.

Vasconcellos et al. (2020) carried out a study in which it quantifies the relative error for some approximation models proposed in the literature. According to Vasconcellos et al (2020) for a relative roughness of approximately 0.005, the model that would present a greater relative error would be the model by Tsal (1989).

In the present work, a comparative analysis for the models of approximation of the Colebrook-White equation (mentioned in section II) was carried out with the experimental data presented by Bandeira (2015).

Figure 2 illustrates the head loss for all models given the same operating condition. It is also observed how the data are plotted for Colebrook-White and Bandeira (2015).

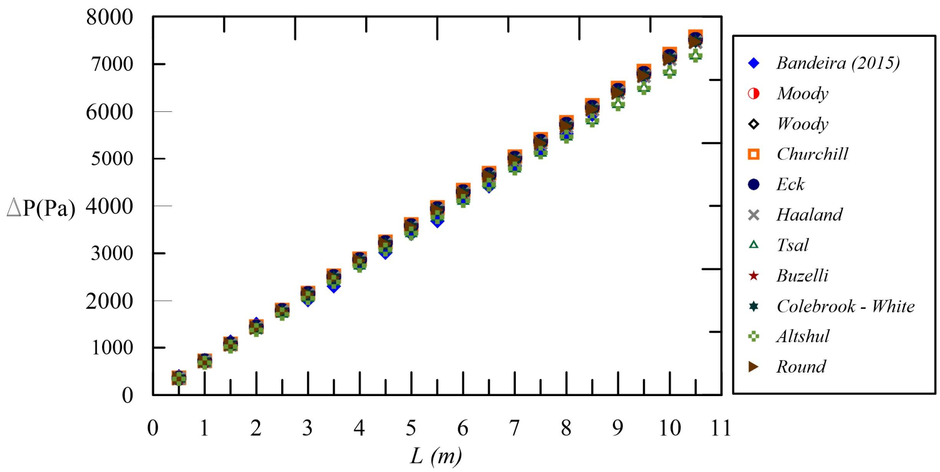

Fig.2. Head loss versus length for each of the models analyzed

It is possible to observe that for all models there is a tendency of behavior towards the head loss and that some models, tend to present more discrepant results as the length increases. Table III is generated by the application of Darcy-Weisbach equation for head loss when parameters in Table I and Table II are considered.

TABLE IIIII
head loss values considering different Colebrook-White approximations for the friction factor

x(m)	Bandeira	Moody	Woody	Churchill	Eck	Haaland	Tsal	Buzelli	Round	Altshul	Colebrook
0.5	399.00	359.69	360.42	360.60	358.20	355.16	341.75	356.30	355.57	341.74	356.01
1.0	740.00	719.38	720.85	721.19	716.41	710.33	683.49	712.60	711.14	683.49	712.03
1.5	1124.00	1079.07	1081.27	1081.79	1074.61	1065.49	1025.24	1068.90	1066.72	1025.24	1068.04
2.0	1504.00	1438.76	1441.70	1442.38	1432.81	1420.65	1366.99	1425.20	1422.29	1366.99	1424.06
2.5	1750.00	1798.45	1802.12	1802.98	1791.02	1775.81	1708.74	1781.50	1777.86	1708.74	1780.07
3.0	2010.00	2158.14	2162.54	2163.58	2149.22	2130.98	2050.48	2137.80	2133.43	2050.48	2136.08
3.5	2304.00	2517.83	2522.97	2524.17	2507.42	2486.14	2392.23	2494.10	2489.01	2392.33	2492.1
4.0	2747.00	2877.52	2883.39	2884.77	2865.63	2841.30	2733.98	2850.40	2844.58	2733.98	2848.11
4.5	3011.00	3237.22	3243.81	3245.36	3223.83	3196.47	3075.73	3206.70	3200.15	3075.73	3204.12
5.0	3411.00	3596.91	3604.24	3605.96	3582.03	3551.63	3417.47	3563.00	3555.72	3417.47	3560.14
5.5	3684.00	3956.60	3964.66	3966.56	3940.23	3906.79	3759.22	3919.30	3911.29	3759.22	3916.15
6.0	4134.00	4316.29	4325.09	4327.15	4298.44	4261.95	4100.97	4275.60	4266.87	4100.97	4272.16
6.5	4416.00	4675.98	4685.51	4687.75	4656.64	4617.12	4442.71	4631.90	4622.44	4442.71	4628.18
7.0	4840.00	5035.67	5045.93	5048.35	5014.84	4972.28	4784.46	4988.20	4978.01	4784.46	4984.19
7.5	5151.00	5395.36	5406.36	5408.94	5373.05	5327.44	5126.21	5344.49	5333.58	5126.21	5340.21
8.0	5533.00	5755.05	5766.78	5769.54	5731.25	5682.61	5467.96	5700.79	5689.15	5467.96	5696.22
8.5	5937.00	6114.74	6127.21	6130.13	6089.45	6037.77	5809.70	6057.09	6044.73	5809.70	6052.24
9.0	6390.00	6474.43	6487.63	6490.73	6447.66	6392.93	6151.45	6413.39	6400.30	6151.45	6408.25
9.5	6710.00	6834.12	6848.05	6851.33	6805.86	6748.09	6493.20	6769.69	6755.87	6493.20	6764.26
10.0	7111.00	7193.81	7208.48	7211.92	7164.06	7103.26	6834.94	7125.99	7111.44	6834.95	7120.28
10.5	7528.00	7553.50	7568.90	7572.52	7522.27	7458.42	7176.69	7482.29	7467.02	7176.69	7476.29

Analyzing Figure 2, it is noticed that for the first three meters, all models converge. It is imperceptible the difference in the graph; however, for values above three meters some data from the models tend to diverge from the experimental and numerical data. To better understand each model, a comparison was made between each approximation model with both experimental and the numerical data, obtained by the Colebrook-White equation. This data will be presented in the following sections.

A. *Comparison of Data Between Colebrook-White and Bandeira (2015)*

When compared, the head loss values obtained by the experimental data and Colebrook-White equation, it is noticed that for lengths between 3 and 8 meters the results diverges. For lengths greater than 8.5 meters experimental data and Colebrook-White equation becomes convergent. A hypothesis for this discrepancy could be due to the effects of turbulent fluctuations that are not modeled in the Colebrook-White equation, which are no longer perceived as the length and head loss increase. The average of the relative error between Bandeira and Colebrook-White is 1.5%. Figures 3 and 4 illustrate the results of the comparison by Colebrook-White and Bandeira (2015).

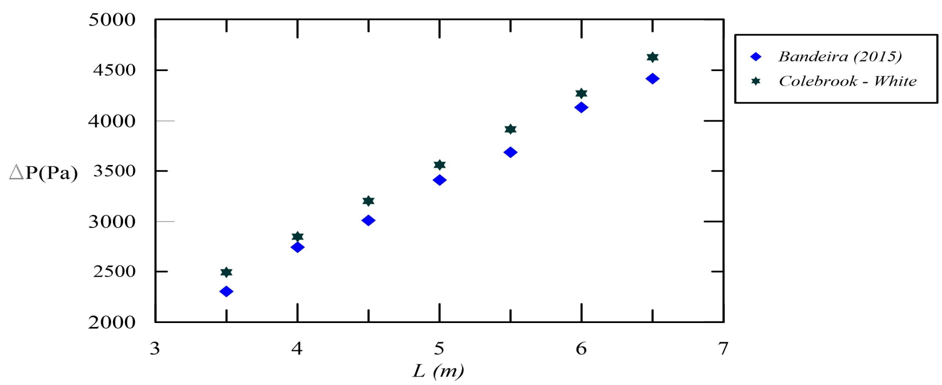

Fig. 3 – Comparison of data between Bandeira (2015) and Colebrook-White for lengths between 3.5 and 6.5 meters.

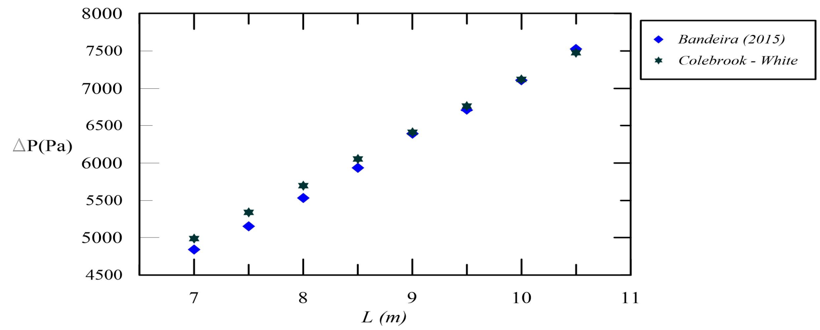

Fig. 4 – Comparison of data between Bandeira (2015) and Colebrook-White for lengths between 7.0 and 10.5 meters.

Figure 4 presents a convergence in head loss with a relative error of 0.15%.

B. Comparison of data between Colebrook – White, Eck and Bandeira (2015)

When comparing the experimental data and the Colebrook-White equation, it is observed that the Eck model shows good convergence with the Colebrook-White model. When compared to the experimetal data, the behavior is similar to that of the previous section. The average of the relative error between Bandeira and Eck is 2.2% and between Eck and Colebrook-White is 0.62%. Figures 5 and 6 illustrate the results of the comparison by Colebrook-White, Eck and Bandeira (2015).

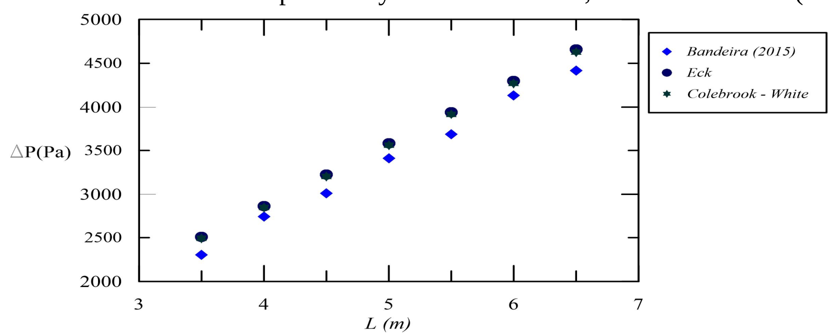

Fig. 5 – Comparison of data between Bandeira (2015), Eck and Colebrook-White for lengths between 3.5 and 6.5 meters.

Figure 6 presents a convergence in the head loss between Ecks model and the experimental data which both of them tend to have the same result when Colebrook-White model is applied. The relative error between Eck and Bandeira (2015) is 0.08% and Colebrook-White and Eck is 0.61%.

C. Comparison of data between Colebrook – White, Churchill and Bandeira (2015)

When compared the experimental data of Bandeira (2015), Churchill model and Colebrook-White equation, it is observed that the Churchill model presents good convergence with Colebrook-White. When compared to the experimental data the behavior is similar to that of the previous section. The average of the relative error between Bandeira and Churchill is 2.85% and between Churchill and Colebrook-White is 1.29%. Figures 7 and 8 illustrate the results of the comparison with Colebrook-White equation, Churchill model and Bandeira (2015).

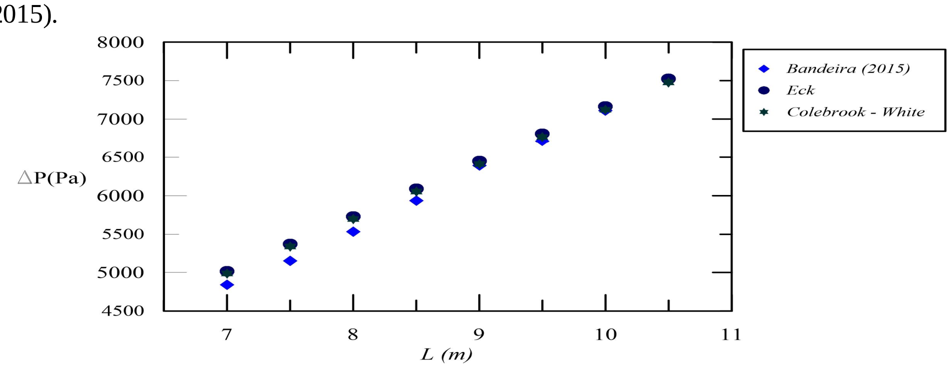

Fig. 6 – Comparison of data between Bandeira (2015), Eck and Colebrook-White for lengths between 7.0 and 10.5 meters.

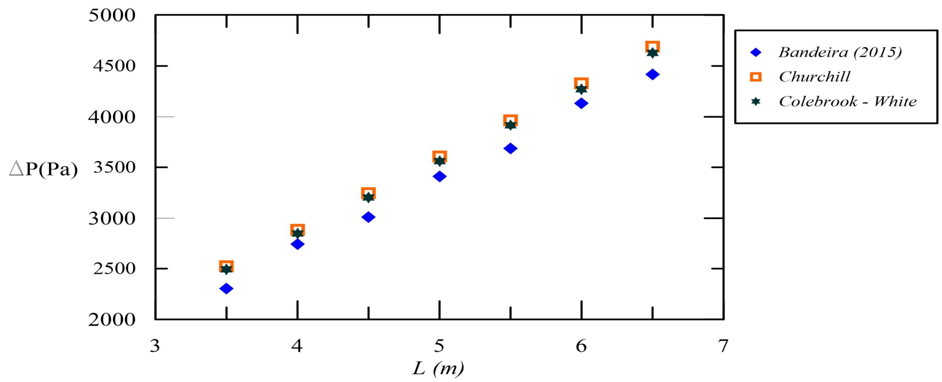

Fig. 7 – Comparison of data between Bandeira (2015), Churchill and Colebrook-White for lengths between 3.5 and 6.5 meters.

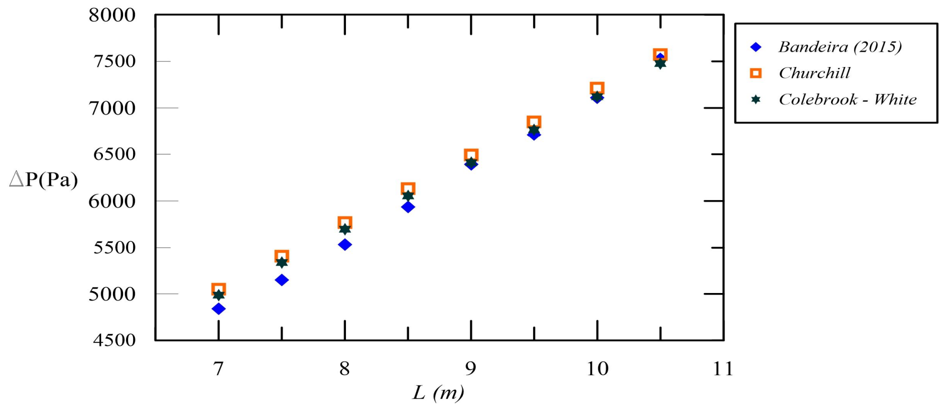

Fig. 8 – Comparison of daa between Bandeira (2015), Churchill and Colebrook-White for lengths between 7.0 and 10.5 meters.

Figure 8 shows that the head loss values between the Churchill model and the experimental data converge with the Colebrook-White model. The relative error between Churchill and Bandeira for the last point is 0.59%, and of Colebrook-White and Churchill is 1.28%.

D. Comparison of data between Colebrook – White, Buzelli and Bandeira (2015)

The comparison of experimental data from Bandeira (2015), Buzelli model and Colebrook-White equation reveals that Buzelli model presents a good convergence with Colebrook-White. When compared with experimental data the behavior is similar to the previous section. The average of the relative error between Bandeira and Buzelli is 1.38% and between Buzelli and Colebrook-White is 0.08%. Figures 9 and 10 illustrate the results of the head loss comparison obtained for Colebrook-White, Buzelli and Bandeira (2015).

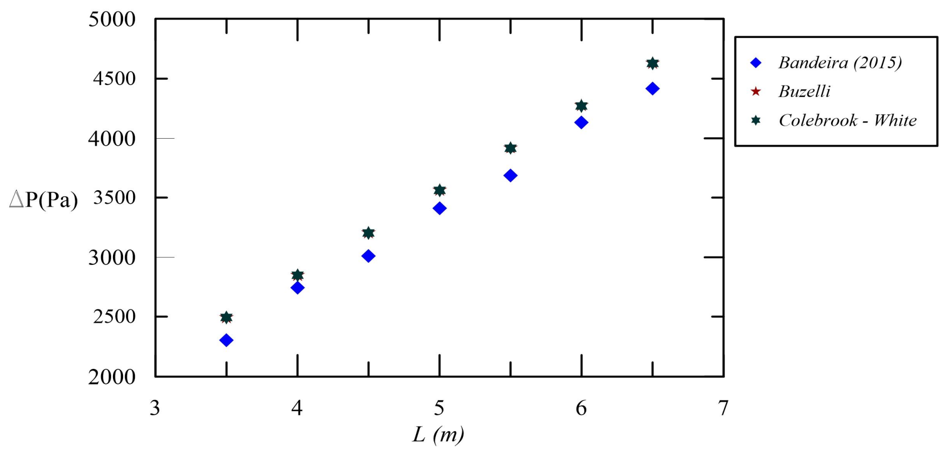

Fig. 9 – Comparison of data between Bandeira (2015), Buzelli e Colebrook-White for lengths between 3.5 and 6.5 meters.

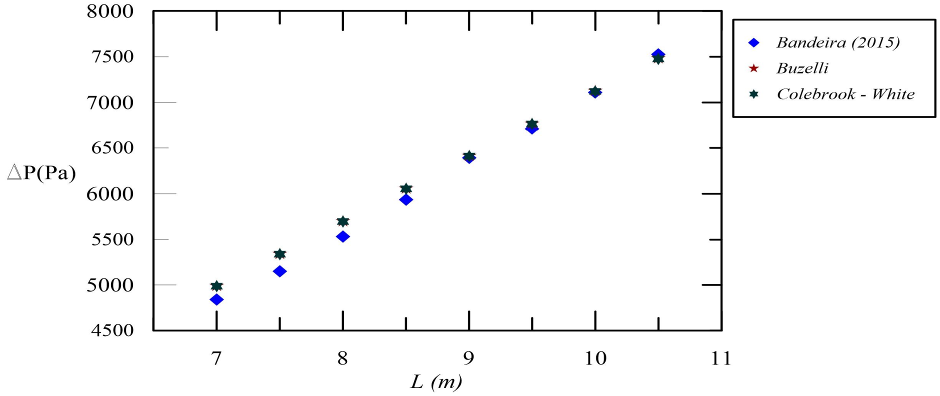

Fig. 10 – Comparison of data between Bandeira (2015), Buzelli and Colebrook-White for lengths between 7.0 and 10.5 meters.

According to Figure 10 the head loss considering the Buzelli model and the experimental data, agree with Colebrook-White model. The relative error between Buzelli and Bandeira for the last point of the graph is 0.60%, and for Colebrook-White and Buzelli is 0.08%.

E. Comparison of data between Colebrook – White, Woody and Bandeira (2015)

The head loss values using Woddy model and Colebrook-White equation show good agreement. When compared the experimental data and the Woody model for the head loss both have similar bahaviour of the previous section. The average of the relative error between Bandeira and Woody is 2.79% and between Woody and Colebrook-White is 1.24%. Figures 11 and 12 illustrate the results of the head loss comparison obtained for Colebrook-White, Woody and Bandeira (2015).

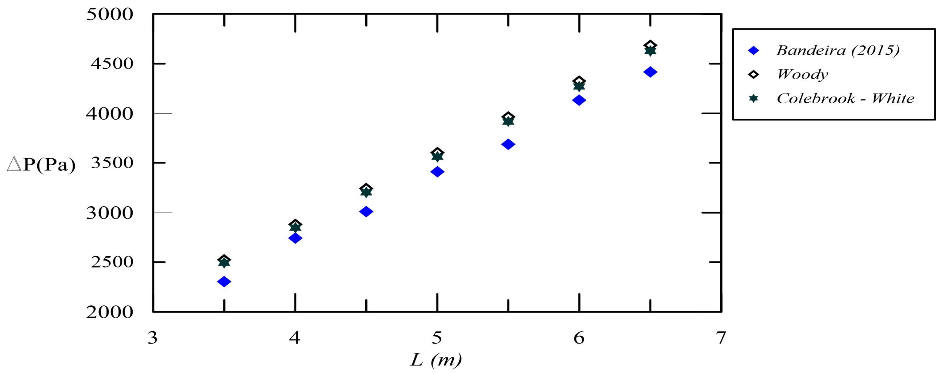

Fig. 11 – Comparison of data between Bandeira (2015), Woody and Colebrook-White for lengths between 3.5 and 6.5 meters.

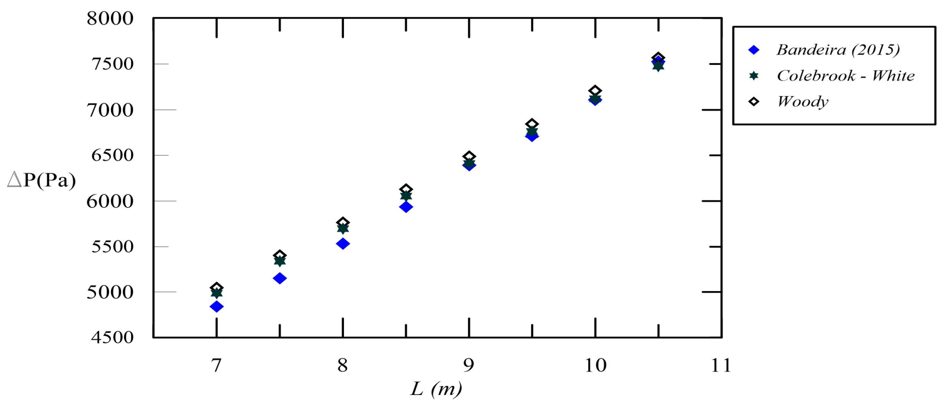

Fig. 12 – Comparison of data between Bandeira (2015), Woody and Colebrook-White for lengths between 7.0 and 10.5 meters.

Figure 12 shows that the head loss using Woody model and experimental data converge with Colebrook-White. The relative error between Woddy and Bandeira for the last point is 0.54%, and for Colebrook-White and Woddy is 1.23%.

F. Comparison of data between Colebrook – White, Tsal and Bandeira (2015)

The Tsal model does not show a good convergence with Colebrook-White when compared to the other models presented in the previous sections. For lenghts from 3.5 to 7.5 meters Tsal model and experimental data converge; however, for values equal or greater than 8.0 is divergent. The average of the relative error between Bandeira and Tsal is 2.53% and between Tsal and Colebrook-White is 4.00%. Figures 13 and 14 illustrate the results of the head loss comparison obtained for Colebrook-White, Tsal and Bandeira (2015). In Figure 14 it is observed that the values of head loss between the Tsal model and the experimental data converge with the Colebrook-White model. The relative error between Tsal and Bandeira for the last point is 4.66%, and for Colebrook-White and Tsal is 4.00%.

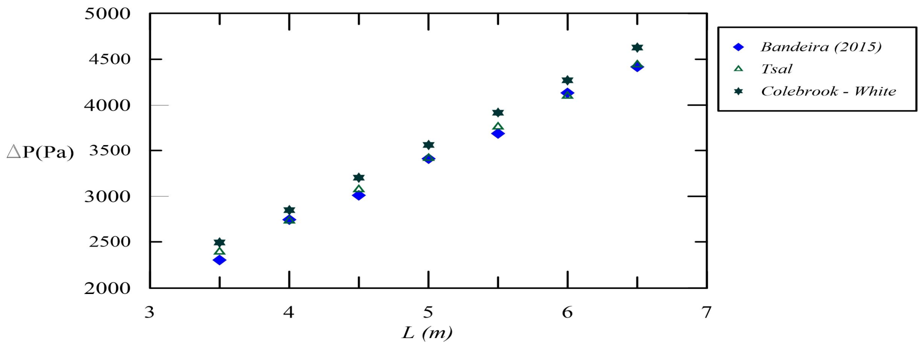

Fig. 13 – Comparison of data between Bandeira (2015), Tsal and Colebrook-White for lengths between 3.5 and 6.5 meters.

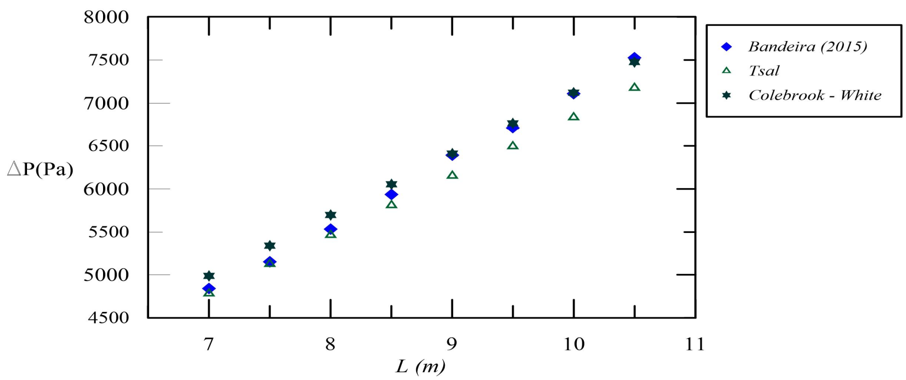

Fig. 14 – Comparison of data between Bandeira (2015), Tsal and Colebrook-White for lengths between 7.0 and 10.5 meters.

G. Comparison of data between Colebrook – White, Moody and Bandeira (2015)

The Moody model and Colebrook-White present good convergence. When compared with the experimental data, results are similar to the previous section. The average of the relative error between Bandeira and Moody is 2.53% and between Moody and Colebrook-White is 1.03%. Figures 15 and 16 illustrate the results of the head loss comparison obtained for Colebrook-White, Moody and Bandeira (2015).

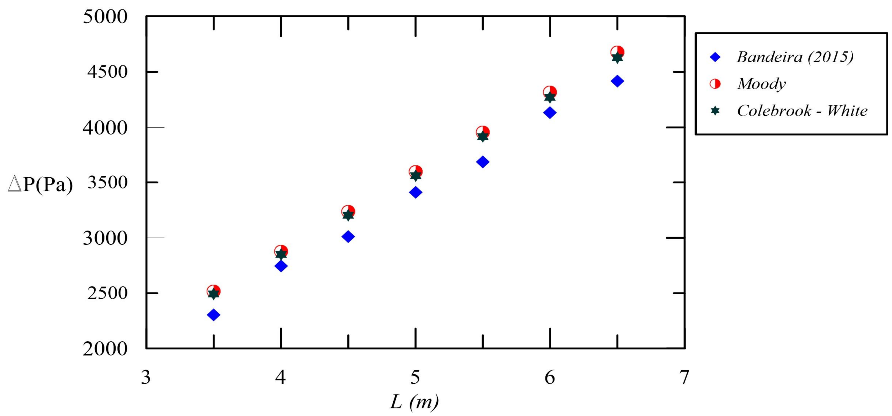

Fig. 15 – Comparison of data between Bandeira (2015), Moody and Colebrook-White for lengths between 3.5 and 6.5 meters.

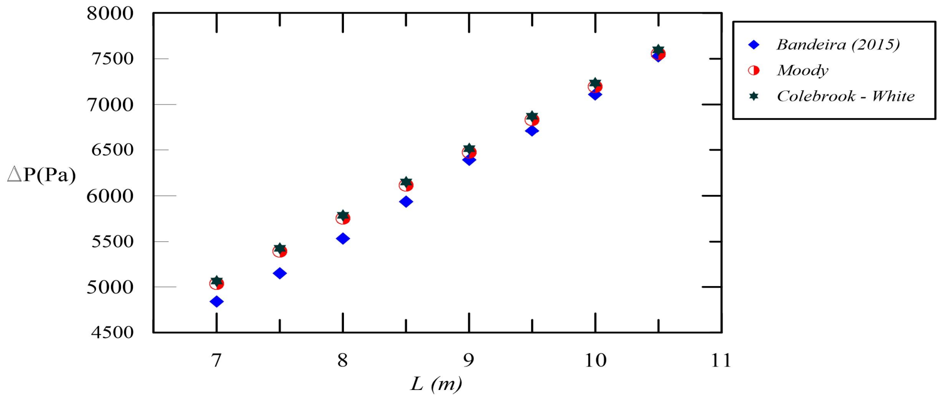

Fig. 16 – Comparison of data between Bandeira (2015), Moody and Colebrook-White for lengths between 7.0 and 10.5 meters.

In Figure 12 the head loss for Moody model and experimental data converge with the Colebrook-White model. The relative error between Moody and Bandeira for the last point is 0.34%, and for Colebrook-White and Moody is 1.03%.

H. Comparison of Data Between Colebrook – White, Haaland and Bandeira (2015)

The head loss considering Haaland model and Colebrook-White equation agree, presenting a good convergence. When compared with the experimental data the behavior shows similarity with previous section. The average of the relative error between Bandeira and Haaland is 1.29% and between Haaland and Colebrook-White is 0.24%. Figures 17 and 18 illustrate the results of the head loss comparison obtained for Colebrook-White, Haaland and Bandeira (2015).

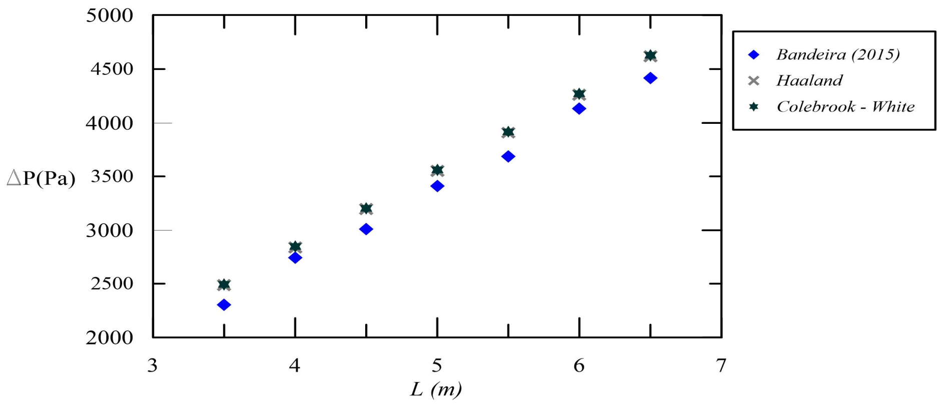

Fig. 17 – Comparison of data between Bandeira (2015), Haaland and Colebrook-White for lengths between 3.5 and 6.5 meters

Figure 18 shows that the head loss values for Haaland model and experimental data converge with Colebrook-White model. The relative error between Haaland and Bandeira for the last point is 0.94%, and for Colebrook-White and Haaland is 0.23%.

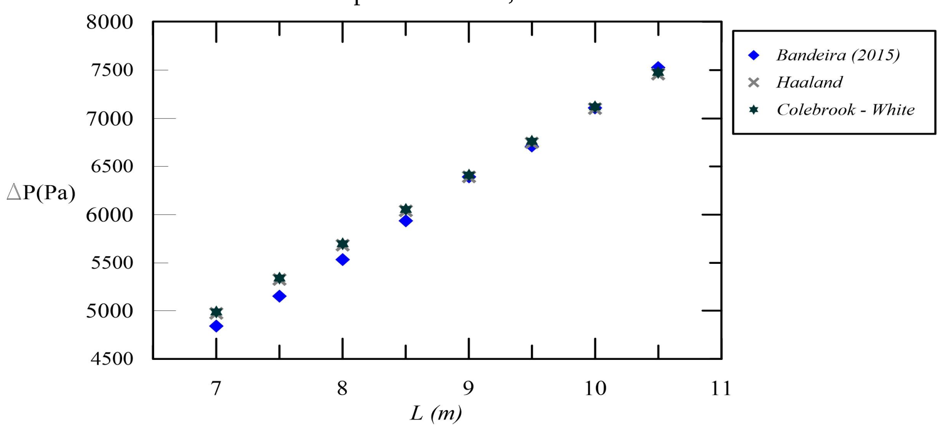

Fig. 18 – Comparison of data between Bandeira (2015), Haaland and Colebrook-White for lengths between 7.0 and 10.5 meters.

I. Comparison of data between Colebrook – White, Altshel and Bandeira (2015)

When compared, the values for head loss with Altshel model and Colebrook-White do not show good convergence as the others sections. When compared with the experimental data from Bandeira (2015) for lengths from 3.5 to 7.5 meters, it is convergent; however, for values of length greater than 8 meters it is divergent. The average of the relative error between Bandeira and Altshel is 2.53% and between Altshel and Colebrook-White is 4.00%. Figures 19 and 20 illustrate the results of the head loss comparison obtained for Colebrook-White, Altshul and Bandeira (2015).

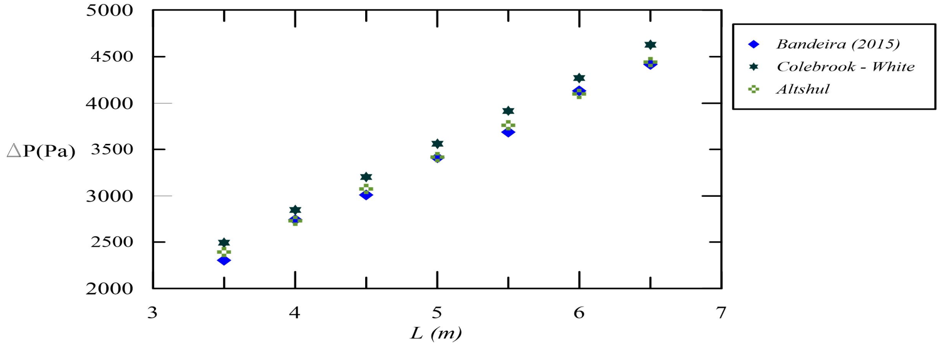

Fig. 19 – Comparison of data between Bandeira (2015), Altshul and Colebrook-White for lengths between 3.5 and 6.5 meters.

Figure 12 shows that the head loss values between the Altshul model and the experimental data converge with the Colebrook-White model. The relative error between Altshul and Bandeira for the last point is 4.67%, and for Colebrook-White and Altshul is 4.00%.

J. Comparison of Data Between COLEBROOK – White, Round and Bandeira (2015)

When comparing the experimental data of Bandeira (2015), the Round model and the Colebrook-White equation, it is observed that the Round model shows good convergence with Colebrook-White. When compared to the experimental data, the behavior is similar to that of the previous section. The average of the relative error between Bandeira and Round is 1.41% and between Round and Colebrook-White is 0.12%. Figures 21 and 22 illustrate the results of the head loss comparison obtained for Colebrook-White, Round and Bandeira (2015).

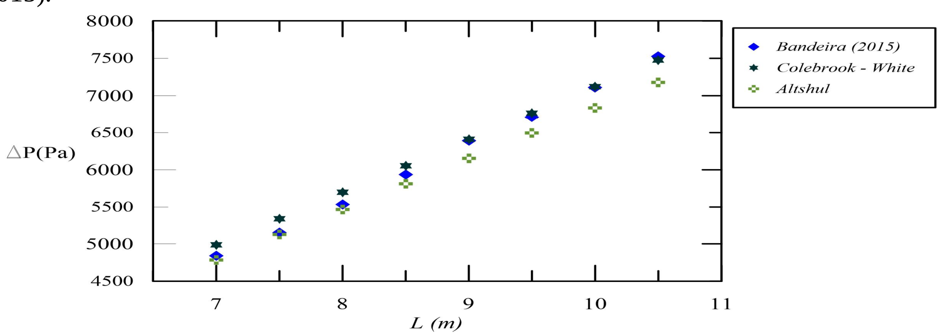

Fig. 20 – Comparison of data between Bandeira (2015), Altshul and Colebrook-White for lengths between 7.0 and 10.5 meters.

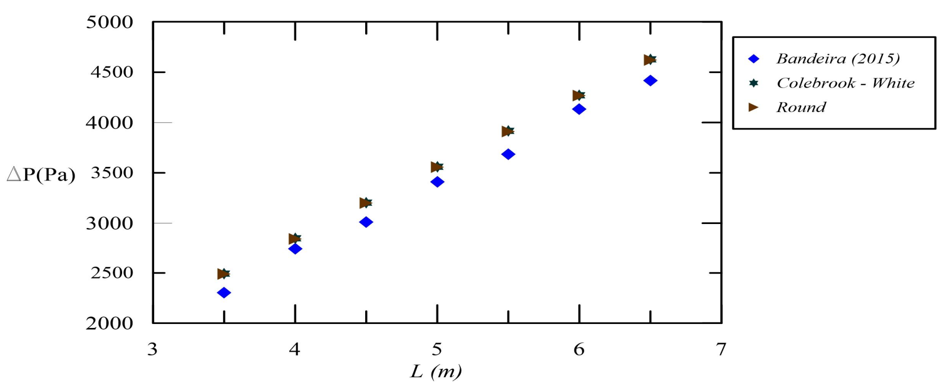

Fig. 21 – Comparison of data between Bandeira (2015), Round and Colebrook-White for lengths between 3.5 and 6.5 meters.

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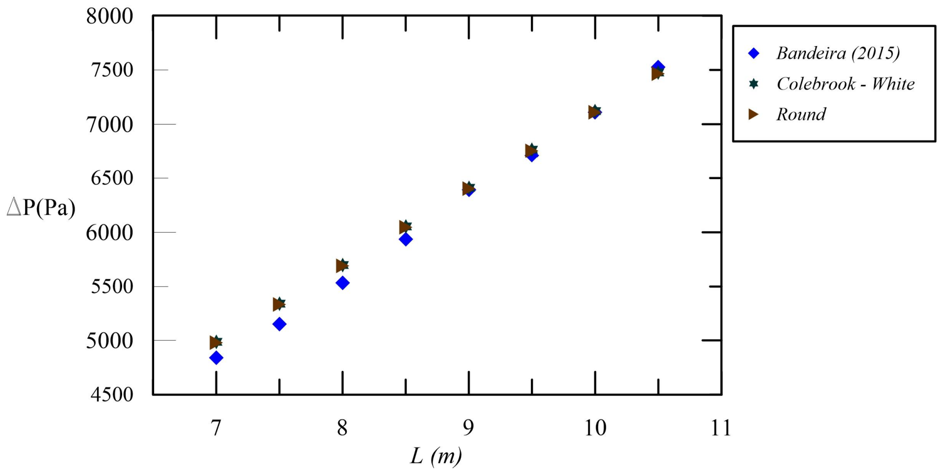

Fig. 22 – Comparison of data between Bandeira (2015), Round and Colebrook-White for lengths between 7.0 and 10.5 meters.

Figure 22 shows a convergence with Colebrook-White model for both values of head loss obtained from the experimental data and Rounds models.

Figure 22, shows that for head loss values between Round model and the experimental data converge with the Colebrook- White model. The relative error between Round and Flag for the last point is 0.81%, and for Colebrook-White and Round is 0.12%.

VI. CONCLUSIONS

The following paper presented comparisons made between experimental data from Bandeira (2015) and Colebrook-White equation, considering nine approximation models used to calculate the friction factor. The conclusions obtained in this work refer to a Reynolds number equal to 36800 and a 14 meters long pipe. This work showed that the analyzed models behaved similarly as presented in literature.

The Tsal and Altshul models were the models that showed the greatest discrepancy when compared to the others, however, it is noteworthy that for lengths less than 8 meters, these models showed a good convergence with the experimental data.

It can be highlighted that Buzellis model presented the best approximation. Such model had very small relative error when compared with the experimental and numerical data of Colebrook-White, the error being in the range of 0.083 to 0.087%.

The results presented in Section V for the relative errors are similar to those presented in Table II. The models that presented the best performances for the simulated experimental condition were those of Eck, Haaland and Buzelli.

For future work, an experimental study with lower and higher Reynolds numbers is suggested to verify that the three models that had the best performance remain having the same results approached in this work.

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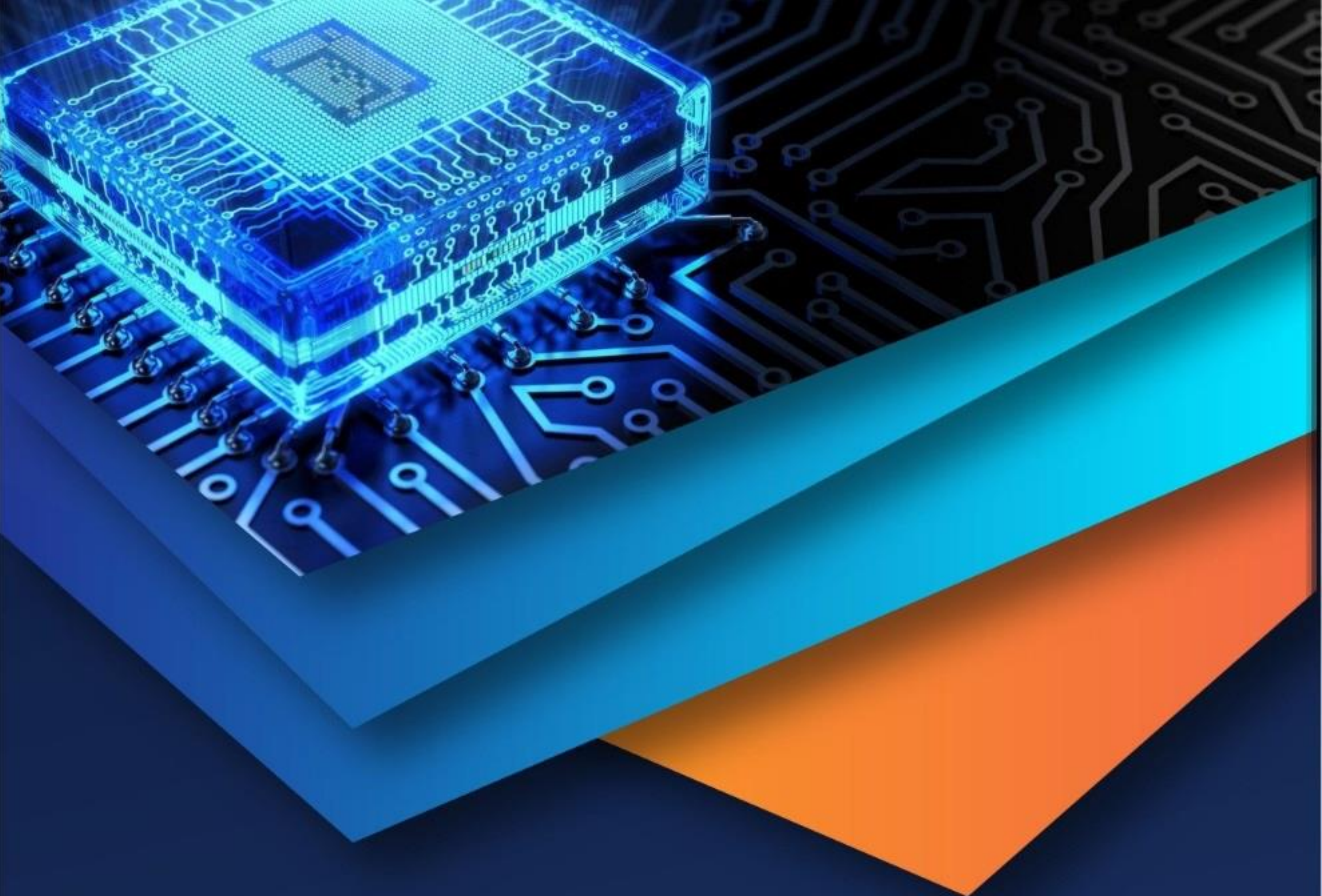

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