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RESEARCH ARTICLE

Turbulent flow in PVC pipes in water distribution systems

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ABSTRACT

Since the incorporation of PVC as pipe material in the second half of 20th century, its use in the design, rehabilitation and expansion of Water Distribution Networks (WDS) has been widely assimilated. However, materials with higher roughness were more commonly used and with these materials were carried out the studies on which are based the most used design equations (Colebrook-White, Darcy-Weisbach and Hazen-Williams). In this work, the applicability of these equations is tested using PVC as the material to verify their precision. Measurements of pressure loss in different assemblies for extents of Reynolds numbers ranging from $3x10^4$ to $5x10^5$ and relative roughness between $6x10^{-4}$ and $2x10^{-3}$ were performed. For small diameters, Blasius and Prandtl–von Kármán equations can be used to calculate the friction factor. On the other hand, for larger diameters, the Colebrook-White equation correctly describes the relationship between the friction factor and the Reynolds number.

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Head losses in PVC pipes; steady flow in pressure conduits; friction factor; turbulent flow; flow resistance

Introduction

Water distribution systems (WDSs) are one of the most important urban infrastructure assets of the society. They are essential for human life in cities and directly affect public health. Therefore, it is vital to understand the hydraulic behavior of WDSs to properly design and operate them. This work is relevant because it addresses to two basic inquiries: (1) the effect of modern materials (PVC) in pipes and in the design of civil infrastructure and (2) if the equations used for calculating the flow characteristics in pipes are adequate or sufficiently precise. Testing precision of friction head loss equations is essential because many researches focus on new methodologies for more precise designs and do not question if the equations for the design problem are sufficiently precise.

The rational empirical study of this work is relevant because the equations used for the design of civil engineering infrastructure date back to the 19th and early 20th century and plastic pipes began to be tested, approved and used globally, in the mid 1960s. Therefore, when the equations were established, no tests were performed in this material and it is not clear if they are precise and should be used for the designs. The misuses of these equations can translate to capacity problems in urban drainage systems and distribution of drinking water, which has serious implications. As mentioned, in a WDS there can be social, economic and health implications regarding the errors in the design of these systems. It is likely that, for the design horizon contemplated, the systems do not fulfill their function due to blunders in the design calculations.

To have an accurate estimation of the flow resistance within the system it is necessary to study the equations used for calculating the flow characteristics in pipes. The most commonly used equations for pipe design are Colebrook-White, Darcy-Weisbach and Hazen-Williams. Although the use of the Hazen-Williams equation is preferred for its ease of operation, since it is explicit for velocity, one must be very careful because it is often overlooked that this equation has limits of applicability (Diskin 1960). In this research, the equations mentioned before are used to calculate the friction factor (f) in a series of laboratory tests to verify their validity.

Darcy-Weisbach Equation (1) is the most general equation for determining friction head losses, and thus, it does not have any limits in its applicability.

$$h_f = f\frac{l}{d}\frac{v^2}{2g} \tag{1}$$

where g is the acceleration of gravity, d is the internal diameter of the pipe, l is the length of the pipe, v is the velocity of the flow through the pipe and f corresponds to the friction factor.

Colebrook and White (1939), on a semi-empirical basis, found a mathematical relationship to describe the behavior of the friction factor in the turbulent flow zone:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{k_s}{3.7d} + \frac{2.51}{Re\sqrt{f}}\right) \tag{2}$$

where f corresponds to the friction factor, Re is the Reynolds number, d is the internal diameter of the pipe and (k_S/d) is the pipe relative roughness. It is important to denote that f, Re and k_s/d are all dimensionless parameters. For smooth pipes, if k_s/d = 0, Equation (2) can be rewritten into the equation proposed by Prandtl-von Kármán. This also applies for rough pipes of uniform roughness, when the value of *1/*Re tends to 0 (Finnemore and Franzini 2002; Quintela 2011).

The Hazen-Williams Equation (3) is shown below:

$$v = 0.849C_{HW}R^{0.63}S^{0.54} \tag{3}$$

where v is the velocity, R is the hydraulic radius, S is the energy loss per length and C_{HW} is the Hazen-Williams coefficient. Some authors have set limits of applicability for this equation:

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Finnemore and Franzini (2002) and Houghtalen, Akan, and Hwang (2010) suggest that the equation applies to pipes with diameters greater than 5 cm and velocities lower than 3 m/s.

Based on contemporary standards for WDSs such as: U.S. American Water Works Association (AWWA 2002), Canadian Design Guidelines for First Nation Water Works (Indian and Northern Affairs Canada 2006), Australian Drinking Water Guidelines (Natural Resource Management Ministerial Council 2011) and Colombian Technical Regulation of the Drinking Water and Basic Sanitation Sector (Ministerio de Vivienda, Ciudad y Territorio 2011), the investigation focuses in the area of the Moody diagram in which real designs are contemplated. In addition, the scope of the research was reduced to PVC pipes with commercial diameters between 75 mm to 250 mm, which represent the composition of secondary water distribution networks in a community (Ministerio de Vivienda, Ciudad y Territorio 2011).

Previous studies

The concern about the difference between modern materials against those used to study the equations that engineers rely on to make their designs is not so recent. For smooth pipes, the experimental determination of roughness k_s is difficult and is usually done by statistical analysis. Diogo and Vilela (2014), citing Lencastre (1996) and Novais-Barbosa (1986), observe that values of the order of 0.002 mm to 0.004 mm or even larger are often reported and commonly used in engineering practice for polyethylene and PVC pipes, and also highlight that aspects regarding the manufacturing processes or the age of the materials are not usually considered in the roughness selection.

Numerous studies have reported that the friction factors observed and the corresponding head losses in the flow carried by plastic pipes are usually lower than those obtained when considering the Colebrook-White equation without absolute roughness. A succinct and suitable review is presented in Diogo and Vilela (2014) in which it is presented a succinct and suitable review. Levin (1972) presented this for very smooth plastic pipes of 20 meters long, with an internal diameter of approximately 210 mm. According to (von Bernuth and Wilson 1989), Norum (1984) and Urbina (1976) tested small polyethylene pipes with internal diameters between 8.9 mm and 21 mm, as well as Paraqueima (1977), who studied polyethylene pipes with internal diameters of 17.6 mm and 15.5 mm, respectively. With respect to high Re numbers, Bagarello et al. (1995) carried out tests on small low-density polyethylene pipes of 100 meters in length and commercial diameters of 16 mm, 20 mm and 25 mm. Cardoso, Frizzone, and Rezende (2008) tested low-density polyethylene pipes with a length of 15 meters and small internal diameters of 12.9 mm, 16.1 mm, 17.4 mm and 19.7 mm.

More recently, Diogo and Vilela (2014) conducted a research in the Laboratory of Hydraulics, Water Resources and Environment of Coimbra University, Portugal, using three assemblies with four types of plastic pipes of different diameters: (1) two old PVC pipes with internal diameters of 17.35 mm and 21.75 mm; (2) a high-density polyethylene (HDPE) pipe with an internal diameter of 53.6 mm; (3) a low-density polyethylene (LDPE) pipe with an internal diameter of 94.5 mm; and (4) crystal PVC pipe with an internal diameter of 35 mm. The results of the tests showed a trend towards the Colebrook-White curve that relates the friction factor with the Reynolds number. Therefore, they confirmed the Colebrook-White equation as an effective tool for determining continuous head losses for water flowing through pressure plastic pipes in turbulent regimes. In addition, for Re up to 1×10^5 and a little less than $1x10^6$, the empirical equations for smooth pipes of Blasius and Scimemi showed an appropriate behavior. This article presents an experimental work that is based on the research work and analysis proposed in Diogo and Vilela (2014). It was performed for PVC pipes of relatively large diameters, such as those that can be normally found in the current public Water Distribution Networks, and develops, expands and confirms the previous results obtained by those authors.

Analysis and empirical methods

An inventory of some secondary distribution networks in Colombian cities was made to confirm the scope of the investigation. Results obtained showed that pipe diameter distribution for different secondary networks is analogous and therefore applicable.

This inventory includes all the materials currently used in WDS in Colombia (ductile iron, asbestos cement, PVC, PVC-U, polyethylene and concrete). The showed diameters in the table correspond to a commercial denomination, they are not the real internal or external diameters of the pipes.

Table 1 shows similar distributions of pipe diameters for secondary networks in different cities, all with a tendency to small diameters up to 150 mm. Additionally, diameters of 50 millimeters exist although the normative does not recommend them (previous versions of the normative allowed them). Other secondary networks from different cities also showed alike pipe distributions.

The Colombian Technical Regulation of the Drinking Water and Basic Sanitation Sector (RAS 2001) also establishes recommendations for the different materials that used in a WDS, as

Table 1. Resume inventory of some secondary distribution networks in Colombian cities. (The represented diameters are commercial and from several materials).

	Barrancabermeja		Bogota (Sector 13)		Bucaramanga (Sector Estadio)		Bogota (Sector 7)		Santa Marta (Sector San Jorge)	
Diameter (mm)	# of pipes	% of total	# of pipes	% of total	# of pipes	% of total	# of pipes	% of total	# of pipes	% of total
50	837	11%	154	2%	958	14%	24	1%	820	46%
75	4571	61%	2993	41%	4444	64%	1099	29%	536	30%
100	958	13%	1858	25%	828	12%	1172	31%	239	13%
150	482	6%	1539	21%	481	7%	939	25%	79	4%
200	338	5%	528	7%	195	3%	295	8%	64	4%
300	271	4%	317	4%	57	1%	250	7%	34	2%

Table 2. Reynolds number range and relative roughness, with ks equal to 0.0015 mm, range in secondary WDS.

	AWWA		RAS		
d (mm)	Re_{max} (-)	Re_{min} (-)	Re_{max} (-)	Re_{min} (-)	k_s/d(-)
75	1.14×10^5	1.12×10^4	4.49×10^5	3.74×10^4	0.000020
100	1.52×10^5	1.50×10^4	5.98×10^5	4.99×10^4	0.000015
150	2.27×10^5	2.24×10^4	8.97×10^5	7.48×10^4	0.000010
200	3.03×10^5	2.99×10^4	1.20×10^6	9.97×10^4	0.000008
250	3.79×10^5	3.74×10^4	1.50×10^6	1.25×10^5	0.000006

well as the range of velocities to guarantee. For networks using PVC, minimum velocity: 0.50 m/s and maximum velocity: 6.00 m/s. Likewise, AWWA (2002) establishes the following range for the velocities in PVC: minimum velocity: 0.15 m/s and maximum velocity: 1.52 m/s.

Using Equation (4) and assuming a temperature of 20°C ($v = 1.003 \times 10^{-6}\ m^2/s$), is possible to calculate the range of Re that is permitted in this type of WDS for diameters of 75, 100, 150, 200 and 250 mm. Similarly, the theoretical relative roughness (k_s/d) can be calculated for each diameter knowing that the absolute roughness (k_s) of the PVC found in literature is 0.0015 mm. The results are shown in Table 2.

$$Re = \frac{vd}{v} \tag{4}$$

Larger diameters were not evaluated due to their meager quantity in percentage founded in secondary networks. In addition, for larger diameters PVC is not a competitive material. Pipes with larger diameters are usually made of concrete, GRP and ductile iron.

As a result, the area of the Moody diagram of interest when working with secondary water distribution networks is enclosed in Figure 1.

Often, this is the expected range when working with very smooth plastic pipes considering the recommendations of velocities for the design of distribution networks.

To perform an analysis of the data obtained at the time of the different tests, it is important to delimit the transition zone in the Moody diagram. For the Hydraulically Smooth Turbulent Flow (HSTF), the Blasius equation is used to calculate the friction factor. Blasius (1912) found that for Re numbers between 5×10^3 and $1x10^5$, the friction factor is calculated with Equation (5).

$$f = \frac{0.316}{Re^{0.25}} \tag{5}$$

On the other hand, Prandtl (1925) found that, for the calculation of the friction factor for both smooth and rough turbulent flow, Equations (6) and (7) could be used, respectively.

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{2.51}{Re\sqrt{f}}\right) \tag{6}$$

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{k_s}{3.7d}\right) \tag{7}$$

According to Colebrook and White (1939), a flow may be classified as HSTF (Hydraulically Smooth Turbulent Flow) when the pipe roughness size is equal to or less than 30.5% of the thickness of the viscous laminar sublayer (δ'). Then, by replacing the pipe roughness with $0.305\delta'$ in the Colebrook-White equation, Equation (8) is obtained.

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{5.21}{Re\sqrt{f}}\right) \tag{8}$$

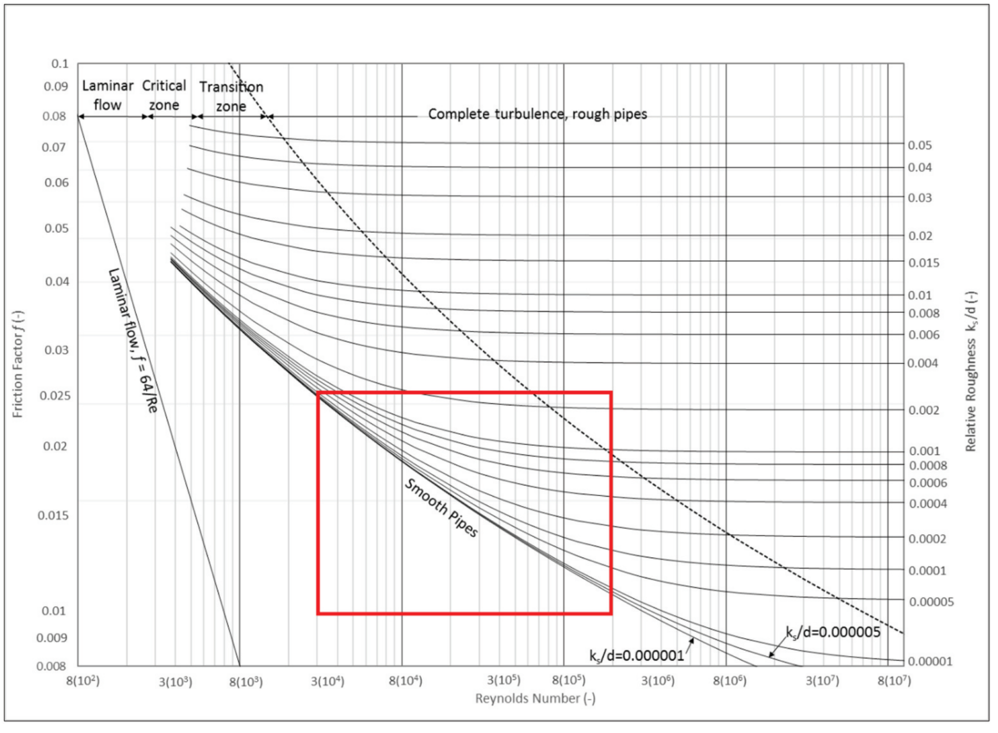

Figure 1. Area of Moody diagram in which secondary WDS designs are contemplated for PCV pipes.

This equation establishes the limit between the hydraulically smooth turbulent flow and the transition turbulent flow in those cases in which the absolute roughness (k_s) is not an absolute value but an equivalent value that represents the random variability of surface roughness in a normal material. For that reason, we did not use Equation 7 because it represents those cases studied by Johann Nikuradse, which used a constant artificial roughness created by fixing sand grains with the uniform diameter with the size is larger than the laminar sublayer thickness (Streeter, Wylie, and Bedford 1998).

Therefore, the equations expressing the hydraulically smoot turbulent flow zone in the Moody diagram are Equations (5), (6) and (8). Equations (5) and (6) are for totally smooth pipes and they represent a theoretical minimum limit for f; they appear as the lower limit on Moody Diagram. On the other hand, Equation (8) represents the upper limit of hydraulically smooth turbulent flow as shown in all figures.

The deductive process of Equation 8 is shown below:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{0.305\delta'}{3.7d} + \frac{2.51}{Re\sqrt{f}}\right) \quad (9)$$

$$\delta' = \frac{11.6v}{v_*} \quad (10)$$

(1) Roughness (k_s) is replaced in Equation (2) with 30.5% of the viscous laminar sublayer (δ ′)

where v is the kinematic viscosity of the fluid and v_*, is the shear rate velocity that is defined as follows in Equation (11):

$$v_* = \sqrt{\frac{\tau_0}{\rho}} \quad (11)$$

where τ_0 is the shear stress and ρ the density of the fluid.

(1) In Equation 9, the thickness of the viscous laminar sublayer is replaced by Equation (10) and Equation (11).

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{0.305}{3.7d}\frac{11.6v}{v_*} + \frac{2.51}{Re\sqrt{f}}\right)$$

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{0.305}{3.7d}\frac{11.6v}{\sqrt{\frac{\tau_0}{\rho}}} + \frac{2.51}{Re\sqrt{f}}\right) \quad (12)$$

$$f = \frac{8\tau_0}{\rho v^2} \quad (13)$$

(1) The relationship between the friction factor and the shear stress is considered as shown in Equation (13).

where v is the mean velocity of the flow.

(1) In Equation (12), the shear stress is replaced by the friction factor, density and average flow velocity (Equation (13))

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{0.305}{3.7d}\frac{11.6v}{\sqrt{\frac{\frac{f\rho v^2}{8}}{\rho}}} + \frac{2.51}{Re\sqrt{f}}\right)$$

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{2.7v}{\sqrt{f}vd} + \frac{2.51}{Re\sqrt{f}}\right) \quad (14)$$

(1) Finally, in Equation (14) the velocity is replaced as a function of the Reynolds number.

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{2.7v}{\sqrt{f}\frac{vRe}{d}d} + \frac{2.51}{Re\sqrt{f}}\right)$$

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{2.7}{Re\sqrt{f}} + \frac{2.51}{Re\sqrt{f}}\right) \quad (15)$$

On the other hand, the upper limit of the transition zone is defined by the HRTF (Hydraulically Rough Turbulent Flow). According to Colebrook and White (1939), this happens when k_s is equal to $6.1\delta'$. Equation (7) and Equation (16) express the upper limit of the transition zone.

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{56.6}{Re\sqrt{f}}\right) \quad (16)$$

Equation (16) is obtained with a deductive similar process to the one of Equation (8) considering$k_s = 6.1\delta'$.

To understand the effect that the new boundaries of the transition zone can present in the Moody diagram, the lower and upper limits of the Colebrook-White equation for the transition zone are plotted based on Equations (8) and (16). In addition, the limits of this zone are also defined considering the Blasius Equation (5) and Prandtl-von Kármán Equations (6) and (7). The delimitation of the transition zone is shown in Figure 2, where the x-axis is on a logarithmic scale, the left y-axis is on a linear scale, and the right y-axis is again on a logarithmic scale.

When comparing the upper limit of the transition zone obtained from the Colebrook-White equation with the Prandtl-von Kármán equation, it is observed that both coincide for all the range of Re. This occurs because of the second term of the parenthesis of the Colebrook-White equation is insignificant compared to the order of magnitude of the first term, as can be seen in the deductive process of Equation (16). For the lower limit, the boundary described by the Blasius equation concurs with what is defined by the Prandtl-von Kármán equation in the limits of applicability that was deduced. On the other hand, in contrast to the upper limit, the lower bound defined by the Colebrook-White Equation (8) differs.

Furthermore, in addition to the empirical analysis made for the equations considering pipe roughness, other widely used equation to analyze here is the Hazen–Williams equation. The reason to do so is that this equation is not appropriate for plastic pipes but, in fact, is commonly and wrongly used. Here the value of the Hazen-Williams coefficient (C_{HW}) must be determined. A relationship between the C_{HW} and f is found using both the Colebrook-White equation and the Hazen-Williams equation was given by Liou (1998); this relation is:

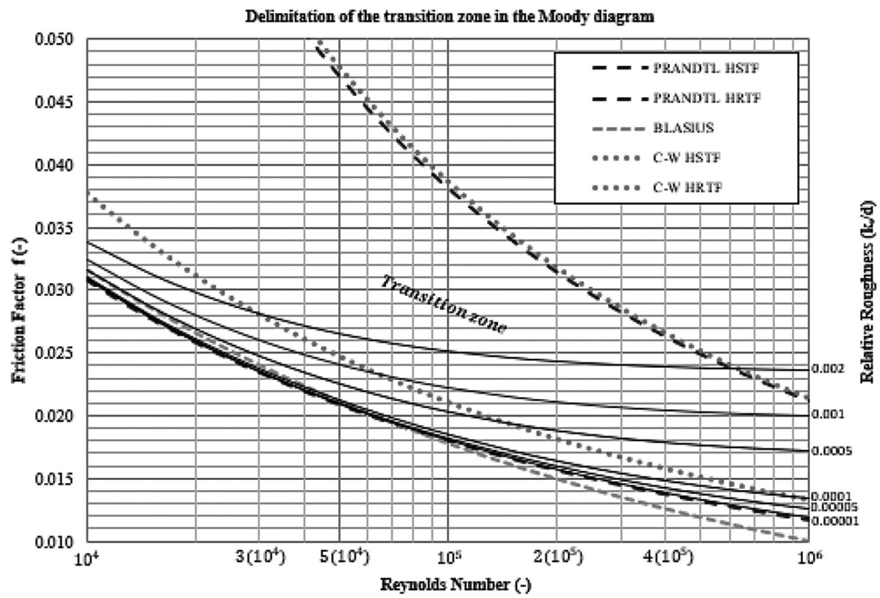

Figure 2. Delimitation of the transition zone in the Moody diagram.

$$C_{HW} = \frac{14.09}{f^{0.54}d^{0.009}\nu^{0.081}Re^{0.081}} \tag{17}$$

Experiments performed

Seven laboratory tests were performed using two different experimental installations located in Bogotá, Colombia. Four tests at the Hydraulic Laboratory of Universidad de Los Andes, and three tests at PAVCO S.A. facilities (a subsidiary enterprise of Mexichem, a Mexican producer of plastic pipes and one of the largest chemicals and petrochemical companies founded in 1953; standard: ASTM D2241) and are schematically represented in Figure 3.

The experimental setup in the Hydraulic Laboratory of Universidad de los Andes is schematically presented in Figure 3(a). The experimental installations consist of an upper tank (distribution tank to all laboratory location), which serves to ensure the stability of the pressure head, a lower tank (storage tank in laboratory underground) and a closed circuit. Water for the lower tank is pumped to the upper tank (14 m above), where a constant head is assured to feed the arrangement. To accomplish this, the pumped discharged to the upper tank must be larger than the discharged send to the test pipe. The excess discharge is transported back to the lower tank through an outflow pipe. The test pipe has 15 mounts that provide stability and avoid vibrations. The supports are adapted to the conditions of the laboratory and placed so that the pipe is kept horizontal. For the differential pressure measurement, there are two KOBOLD sensors (MAN-SD reference) with a measuring range of 0–1 bar and an accuracy of ± 0.5%. A portable ultrasonic measurer (Ultraflux UF 801-P) is used for measuring velocities. This equipment has a measuring range between 1 mm/s and 45 m/s, for external diameters between 10 mm and 10 meters, with an accuracy of ± 0.5%. In addition, a Dwyer digital thermometer (WT-10 model) measures temperature with a range between −40°C and 200°C and accuracy of ±0.1°C. Two gate valves regulate the flow that goes through the test pipe.

The experimental setup in PAVCO facilities, Figure 3(b), consists of a test PVC pipe in which the tests are carried out, a pipe that transports the water from the storage tank to an elevated

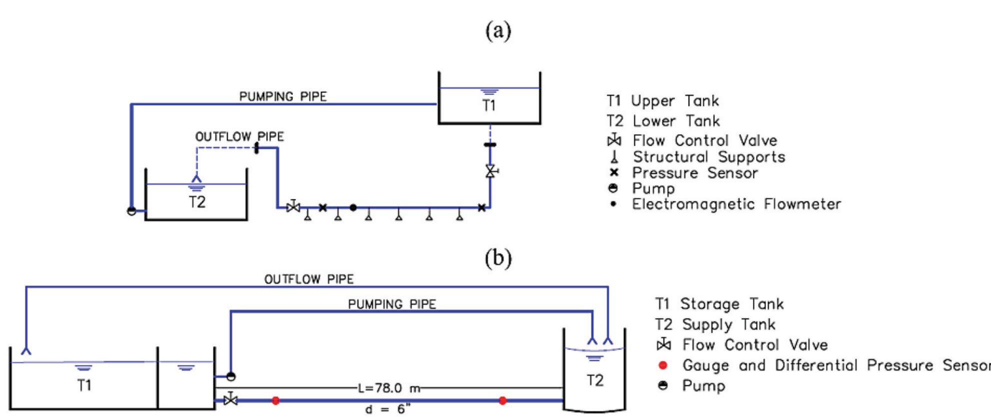

Figure 3. (a) Schema of experimental setup at Universidad de los Andes. (b) Schema of experimental setup at PAVCO S.A facilities.

tank (PVC, internal diameter 203.2 mm), and an overflow pipe (PVC, internal diameter 160.86 mm). There were three test pipes in molecular bi-oriented PVC as shown in Table 3. The supply tank creates a 6 meters head at the entrance of the test pipe. This tank is connected to a second pipe that reaches another tank that fulfills two functions: (1) measures the flow carried and (2) stores water in the system guaranteeing constant piezometric height to produce permanent steady flow. The flow measurement is done electronically, using a sharp-crested weir, and the storage is designed so that the system is fed continuously by a pumping system, which allows to maintain a constant redundant flow, avoiding water waste. Additionally, the system is properly instrumented with electronic measurers to facilitate pressure and flow measurements, guaranteeing accuracy and redundancy in them. The instrumentation used consists in a KOBOLD differential pressure sensor (PAD reference) and a measurement range of 0–375 mbar with ± 0.075% accuracy, a flowmeter at the outlet of the test pipe with an accuracy of ± 0.40%, and a thermometer with an accuracy of ± 0.1°C.

A description of the seven tests performed is shown below:

- The first test (PAVCO facilities) consisted of a main biaxial PVC pipe of 78 meters long, with an internal diameter of 161.28 millimeters (without joints).
- The second test (PAVCO facilities) differs from the first one as the no-junction (NJ) pipe is replaced with a pipe with the same diameter but with 13 joints (WJ). The spacing between joints is 5.85 meters. The type of joint is *spigot-bell* and is used to study the influence of fittings on the hydraulic flow. The instrumentation is maintained the same as for the first model.
- The third test, carried out at the Hydraulic Laboratory of the Universidad de los Andes, consists in a biaxial PVC pipe of 12 meters in length, without joints (NJ), and a - 161.28 mm of real internal diameter. At the end is located a gate valve to regulate the flow that goes through the 161.28 mm real diameter pipe. In addition, two grids, with 161.28 mm in diameter and 1 cm thick, were used to uniformize flow inside the main pipe and ensure uniform flow conditions.
- For test 4 (Hydraulic Laboratory), a biaxial PVC pipe is used with a real diameter of 107.9 millimeters. The length of this experimental installation is maintained (12 meters), but spigot-bell joints are used (WJ). The original pipe is removed and reductions are placed at the beginning and end of the pipe. The valve is at the end of the pipe, and the drainage system is the same as mentioned for test 3.
- In test 5 (Hydraulic Laboratory), a pipe of 107.9 millimeters of the real diameter without joints (NJ) and 12 meters long was used. Unlike the other tests, the flow control valve is located at the beginning of the pipe. At the end of the assembly, there is located an open tank. For the determination of the flow, an electronic measuring device is used.
- For test 6 (Hydraulic Laboratory), a bonding PVC pipe of 81.84 mm real diameter, with no joints (NJ), and 12 meters in length is used. The control valve is placed at the end of the test pipe. For this model, a KOBOLD sensor (PAD reference) and a measurement range of 0–75 mbar, with accuracy, up to ±0.075%.
- For the third PAVCO test (test 7), and last test performed, the PVC pipe has an internal diameter of 209.42 mm and is 78 meters long. The same amount and distribution of fittings is maintained as described in the second test (WJ), as well of the instrumentation used in the first two tests.

Table 3 provides a summary of the laboratory tests previously described.

Results, analysis and discussion

For each test, the value of the friction lossesh_f is measured as the difference of pressures recorded between the two points where the piezometers are. In the assemblies that have joints (*spigot-bell*), to find h_f it is necessary to consider the contribution from minor losses h_m. These minor losses were calculated using a loss coefficient of 0.01 (measured in other assemblies of the Hydraulic Laboratory) per each one of the joints in the assembly. The minor losses (h_m) were computed and removed from the measured total losses ($h_f + h_m$) in order to obtain the friction losses (h_f) and then to calculate the friction factor for all the cases. It is important to say that in all the tests pipelines minor losses were up to 0.25% of friction losses in the worst scenario. Knowing the geometry of the pipe and the flow velocity that is related to the flow rate recorded in each test, the friction factor f can be found for each test, as well as the Re number. With the relation between the friction factor f and the Hazen-Williams coefficient C_{HW}, it is calculated the value of this coefficient for each test. On the other hand, the k_s and C_{HW} are calculated from a simple average for all the results performed in each pipe. A summary of the results is presented in Table 4.

The temperature range of water in which the tests were performed is very stable, no temperature exceeds 23°C and no one is below 16°C. The range of flow rates has varied

Table 3. Summary of the laboratory test characteristics.

Laboratory Test	External Diameter (mm)	Real Internal Diameter (mm)	Wall Thicknesses (mm)	Distance between piezometers (m)	Characteristics
PAVCO S.A (150 – NJ)	168.70	161.28	3.71	66.08	No joints
PAVCO S.A (150 – WJ)	168.70	161.28	3.71	71.24	13 joints
Hydraulic Laboratory (150 – NJ)	168.70	161.28	3.71	11.77	No joints
Hydraulic Laboratory (100 – WJ)	114.66	107.9	3.38	8.42	2 joints
Hydraulic Laboratory (100 – NJ)	114.66	107.9	3.38	9.51	No joints
Hydraulic Laboratory (75 – NJ)	88.82	81.84	3.49	9.11	No joints
PAVCO S.A (200 – WJ)	219.08	209.42	4.83	73.68	13 joints

Table 4. Summary of results for each test.

Test			T (°C)	Q (l/s)	h_f (m)	Re (-)	*f* (-)	k_s (mm)	C_{HW} (-)
1	78 m 150 mm (NJ)	Minimum	16.3	8.24	0.0704	6.26E+04	0.0152	0.0353	146.4
		Maximum	20.8	51.02	1.9999	3.70E+05	0.0209		
2	78 m 150 mm (WJ)	Minimum	16.4	8.32	0.0677	6.33E+04	0.0148	0.0231	151.0
		Maximum	20.2	49.99	2.0992	3.83E+05	0.0199		
3	12 m 150 mm (NJ)	Minimum	16.8	9.20	0.0145	6.06E+04	0.0171	0.0334	146.7
		Maximum	20.2	33.97	0.1794	2.18E+05	0.0198		
4	12 m 100 mm (WJ)	Minimum	20.4	5.58	0.0292	6.05E+04	0.0167	0.0109	149.4
		Maximum	22.1	11.35	0.1064	1.24E+05	0.0209		
5	12 m 100 mm (NJ)	Minimum	19.9	5.41	0.0305	6.04E+04	0.0135	0.0109	151.1
		Maximum	23.0	49.81	1.8012	5.59E+05	0.0210		
6	12 m 75 mm (NJ)	Minimum	18.7	4.29	0.0789	6.06E+04	0.0161	0.0075	150.5
		Maximum	21.2	14.60	0.7021	2.04E+05	0.0209		
7	78 m 200 mm (WJ)	Minimum	16.5	5.11	0.0101	2.86E+04	0.016	0.0706	143.3
		Maximum	18.5	45.81	0.5093	2.58E+05	0.0257		

considerably, and consequently, Re number as well. Test 6 has the smallest flow value registered, 4.3 liters per second and a Re number of 6.06×10^4. Test 1 has the largest flow rate, reaching up to 51 liters per second, Re number of 3.7×10^5. Even with this considerable flow ranges, changes in temperature, diameter and type of experimental setup, all the data obtained are in the HSTF regime. Another parameter that is calculated with the data obtained is the mean Hazen-Williams coefficient and the mean roughness of the PVC. The mean roughness presents a great variation when compared to the values registered in the literature for the PVC (0.0015 mm).

Through Figure 4(a–e), the Moody Diagram is shown with the graphical results of the data obtained for all the tests performed. The graph results are presented form smallest to largest diameter.

In Figure 4(a), it is shown that for the 81.84 mm real diameter pipe, the results tend to the limit established by Prandtl von Kármán for HSTF. For this test, the Re number does not exceed 2×10^5 ($v = 2.78$ m/s). Figure 4(b) shows that for Re numbers between 6×10^4 and 1.2×10^5 ($v = 0.59$ m/s – 5.45 m/s), the trend for a 100 mm commercial diameter PVC pipe (107.9 mm real internal diameter) is similar with and without joints. Although it was tested Re numbers up to 5×10^5 for pipes without joints, this region of the Moody diagram cannot be compared since, for pipe with joints, this range is not covered. However, it is possible to see that for the entire test range, collected data trend is towards the boundary of Prandtl von Kármán.

From Figure 4(c,d) it is observed that for pipes of 150 mm of commercial diameter (161.28 mm real internal diameter), the tendency is towards the limit established by the Colebrook-White equation for HSTF. This trend is clearer when working with high Re numbers (greater than $1x10^5$; $v =$ 0.7 m/s). Figure 4(e) shows the transition that occurs when working with very low and very high Re numbers. Towards lower flows, the graph tends towards the Prandtl von Kármán Smooth Turbulent Flow limit, while for higher Re number this change, and tends toward the Colebrook-White Smooth Turbulent Flow limit. For larger diameters, the trend is most evident toward the Colebrook-White limit.

Figure 5 shows that, in general, for smaller diameters, the friction factor tends towards the Prandtl von Kármán limit, while for larger diameters (greater than 161.28 mm in diameter) the trend tends toward the Colebrook-White limit, for the whole

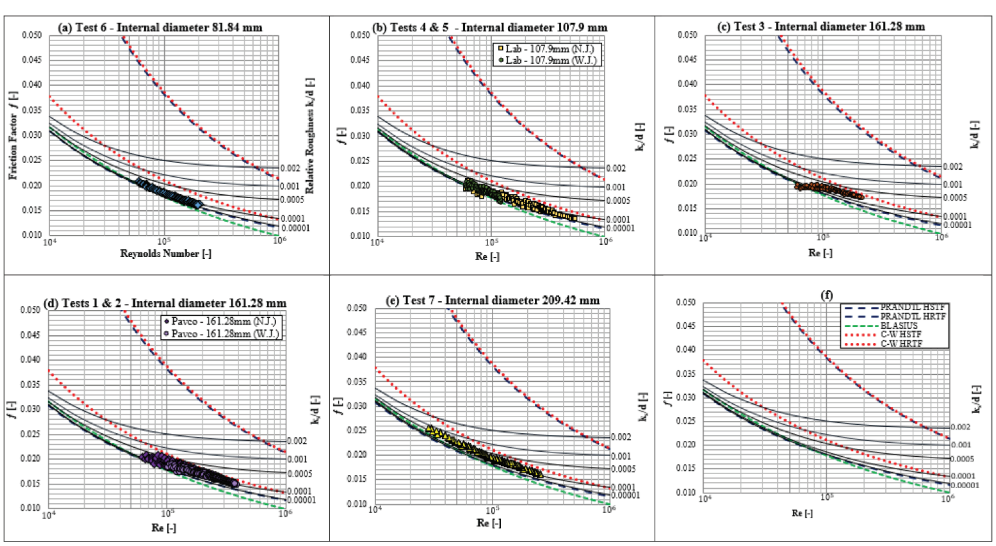

Figure 4. (a) Test 6 – results of 123 tests for PVC pipes with an internal diameter (*d*)of 81.84 mm and 66.08 m long (no joints). (b) Test 4 & 5 – results of 145 tests of $l = 9.51$ m (no joints) and 132 tests $l = 8.42$ m (with joints) for $d = 107.9$ mm. (c) Test 3 – results of 198 tests $d = 161.28$ mm and $l = 11.77$ m (no joints). (d) Test 1 & 2 – results of 250 tests of $l = 66.08$ m (no joints) and 296 tests of $l = 71.24$ m (with joints) for $d = 161.28$ mm. (e) Test 7 – results of 186 tests $d = 209.4$ mm and $l = 73.68$ m (with joints). (f) Moody Diagram with the limits established by the proposed equations of different authors.

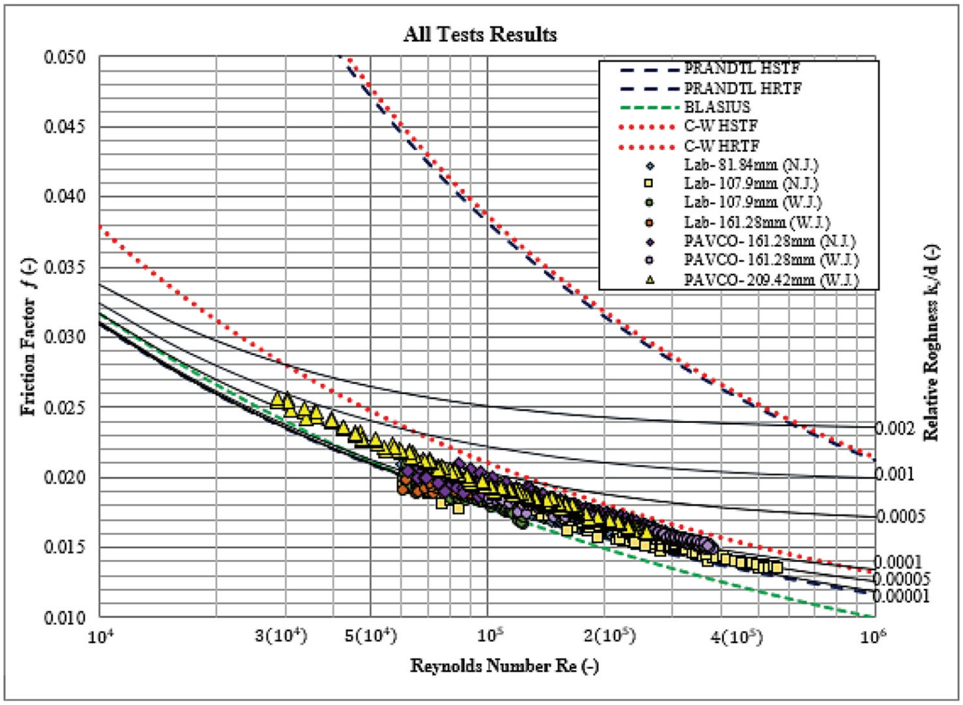

Figure 5. All tests results.

range of Re number in which the data were collected. In addition, it is clear that for low Re numbers, there is no clear trend. The dispersion in this zone may be due to the underestimation of the pressure loss read by the sensors. This variation in the pressure difference may also lead to an underestimation of the friction factor and, hence, of relative roughness.

Conclusions

It is normal to question the materials implemented in finding the design equations most used for the design of potable water distribution networks. More modern and smoother materials are being used every day, with the incorporation of thermoplastic materials and smoother composite materials. In this research, the existence of HSTF in PVC pipes that are in the design range for secondary drinking water distribution networks is verified based on the limits established by the proposed equations of different authors.

For a Reynolds number range between 5×10^4 and $5x10^5$, it can be concluded that: for small diameters, the Prandtl von Kármán equation (Equation 6) has an adequate behavior because allows a good approximation when relating the friction factor (*f*) with the Reynolds number (*Re*), while for larger diameters this relationship is best described by the Colebrook-White Equation. This conclusion is relevant because the Prandtl von Kármán HSTF equation does not use the pipe roughness for the calculation of the friction factor; hence, it could be irrelevant the estimation of pipe absolute roughness for the design. Regarding the presence of joints, it is important to say that they were not a factor that greatly affected friction head loss in all tested PVC pipes.

For the discharges range used in this research, Hazen-Williams coefficients show a large variation of about ±12% for a mean value. This precision is even less for Reynolds numbers outside of those used in this research, this allows us to conclude that Hazen-Williams equation should not be used in plastic pipes.

Even though the materials used for this study are smoother than the ones to postulate the equations that are currently used for the estimation of the friction factor, the results show that traditional equations allow a good approximation to calculate the friction factor. This can be seen in the information shown, since all the experimental data is located between the Prandtl von Kármán and Colebrook-White limits, confirming that the last one, is the most powerful tool for determining head loses.

With the advancement in new materials and more powerful tools for data collection, it is essential that new tests be carried out to corroborate the results attained. By obtaining even more accurate data, it will be possible to carry out a more detailed and precise analysis of the information, thus recreating conditions for a better understanding of the reality that occurs in potable water distribution networks. It is recommended that new tests be performed, and other modern materials are tested, obtaining even more significant results capable of reaffirming that the equations that have been used since the 1920s for the design of WDNs are correct and precise.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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