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Internal surface roughness of plastic pipes for irrigation

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Key words:
friction factor
head loss
roughness meter

ABSTRACT

Assuming that a roughness meter can be successfully employed to measure the roughness on the internal surface of irrigation pipes, this research had the purpose of defining parameters and procedures required to represent the internal surface roughness of plastic pipes used in irrigation. In 2013, the roughness parameter Ra, traditional for the representation of surface irregularities in most situations, and the parameters Rc, Rq, and Ry were estimated based on 350 samples of polyvinyl chloride (PVC) and low-density polyethylene (LDPE) pipes. Pressure losses were determined from experiments carried out in laboratory. Estimations of pressure loss varied significantly according to the roughness parameters (Ra, Rc, Rq, and Ry) and the corresponding pipe diameter. Therefore, specific values of roughness for each pipe diameter improves accuracy in pressure losses estimation. The average values of internal surface roughness were 3.334 and 8.116 μm for PVC and LDPE pipes, respectively.

Palavras-chave:
fator de atrito
perda de carga
rugosímetro

Rugosidade interna de tubos plásticos utilizados em irrigação

RESUMO

Objetivou-se, no presente estudo, estabelecer os parâmetros de amplitude das irregularidades da superfície interna de tubos plásticos para irrigação, assim como procedimentos para sua obtenção e representação utilizando-se um rugosímetro de bancada. Durante o ano de 2013 foram avaliados 350 perfis de rugosidade de tubos de PVC e polietileno de baixa densidade (PEBDL), sendo determinados os parâmetros de rugosidade Ra, clássico para a representação das irregularidades de superfícies na maioria das situações, além dos parâmetros adicionais Rc, Rq e Ry. Determinações hidráulicas de perda de carga foram realizadas em laboratório para comparação com a perda de carga obtida pela aplicação dos parâmetros de rugosidade. Evidenciou-se diferença significativa de desempenho estatístico dos parâmetros de rugosidade (Ra, Rq, Rc e Ry) de acordo com o diâmetro do tubo e, portanto, constatou-se que a adoção de valores de rugosidade específicos para cada diâmetro contribui para a exatidão das estimativas de perda de carga. A rugosidade média para tubos de PVC e PEBDL foi 3,334 e 8,116 μm, respectivamente.

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INTRODUCTION

The roughness of the internal surface of pipes is an important parameter in the estimation of head loss (Bagarello et al., 1995; Brkić, 2011), especially when accuracy is a prerequisite. Bench-top roughness meters are instruments used to measure surface roughness. These instruments operate along with a computer application that generates reports, listing various parameters that express the roughness of the evaluated surface. The parameter that best represents the roughness of the evaluated surface, in general, is specified in technical norms and, therefore, depends on the tested material. It is common the existence of such norms in the mechanical and automotive sector. However, there are no norms or procedures defined for the determination of roughness of plastic pipes used in irrigation. Usually, roughness is obtained according to the material that constitutes the pipe, using tables (Porto, 2006; Bernardo et al., 2006).

Considering the alteration in the material and manufacturing processes and the absence of determinations of internal surface roughness of irrigation pipes, it was assumed that the values in the literature could be outdated and do not reflect precisely the roughness of current commercial pipes. Given the need of choice of the roughness parameter that best represents the amplitude and form of the irregularities on the internal surface, the general objective of the present study was to determine the values of the internal surface of plastic pipes used in irrigation, through a bench-top roughness meter, and describe the roughness of polyvinyl chloride (PVC) and low-density polyethylene (LDPE) pipes based on the use of this device.

MATERIAL AND METHODS

A computer application connected to the roughness meter generates reports listing various parameters able to express the roughness of the evaluated surface. Each parameter expresses surface roughness using a mathematical function that contains variables and coefficients associated with the analyzed profile. The mean roughness (Ra) is the classical parameter to represent roughness adopted in most situations. The parameter Rq represents the square root of the sum of squared deviations, thus being always higher than Ra. The parameter Rc refers to the mean amplitude of the heights of the irregularities in the profile and is represented by the mean of five cut-off values (λ), while Ry is the maximum height of peaks and valleys between these five values (Gadelmawla et al., 2002).

Since the isolated parameter Ra does not characterize well situations with valleys and peaks in high frequency (Sedlaček et al., 2012), the parameters Rq, Rc and Ry were also evaluated, allowing to emphasize the peaks and valleys in the measured profile, besides the form of the irregularities. Farshad et al. (2001) adopted the parameters Ra, Rq, Ry, R_{ZD} and R_{3Z} to study the roughness of internally coated pipes used in the petroleum industry. These authors claim that, although there are other parameters to estimate the roughness of surfaces, the previously cited ones are the most adequate for applications involving flow in pipes.

The study was carried out at the Laboratory for Tests of Irrigation Material (LEMI), linked to the National Institute of Science and Technology - Irrigation Engineering (INCT-EI/ESALQ/USP), in Piracicaba, SP, Brazil. In all, 350 roughness profiles were evaluated for LDPE and PVC pipes, whose characteristics are defined in Table 1.

The roughness of the internal surface of the pipes was measured using a bench-top roughness meter (Mitutoyo, model Surftest SV-624). The device is basically composed of diamond probe tip whose transverse section radius and tip angle are 2.0 μm and 60°, respectively. The instrument was set to move at a constant speed of 0.1 mm s^{-1} on the internal surface of the pipes, with five cut-off values (λ = 2.5) and 9600 sampled points, resulting in 15 mm for evaluation length, since the device disregard 1/2λ at the beginning and at the end of the sampling for reading stability.

The PVC pipes were cut in equidistant points to form cylindrical or semi-cylindrical test units, with length of 5 cm. Roughness was evaluated using five determinations in different positions equidistantly spaced by 1.0 m, for a same pipe, disregarding 1.0 m at the beginning and at the end of the bar of the pipe, with five replicates from a random lot of a single manufacturer. Thus, 25 test units (5 positions x 5 replicates) were used in the determinations for each diameter, totaling 75 determinations for PVC in each direction (longitudinally and transversely to the flow direction). For LDPE pipes, from a single manufacturer, the procedure was similar to that for PVC, but with spacing of 3.5 m between sampling points, disregarding the same length at the beginning and at the end of the line, with four replicates. This sampling procedure resulted in 100 determinations (5 positions x 5 diameters x 4 replicates) for LDPE in each scanning direction.

The roughness meter was daily gauged, before the measurements, using a standard plate provided by the manufacturer. In general, roughness measurements use mathematical filters to separate the components of roughness and undulation (Boryczko, 2013). For that, a threshold wavelength or cut-off value (λ) of 2.5 mm was established based on the NBR ISO 4287 (ABNT, 2002), and this parameter has the function of filtering and excluding the influence of undulation on the determination of the roughness profile (Zeng et al., 2011).

The obtained values of roughness were used in the equation of Swamee (1993) to calculate the friction factor (f) (Eq. 1), valid for the regimes laminar flow, hydraulically smooth turbulent flow, transitional flow and rough turbulent flow (Porto, 2006). The head loss in the LDPE pipes was

Table 1. Nominal diameter (DN), internal diameter (D_i), pipe wall thickness (e) and pressure class of the evaluated pipes (PN)

Material	DN	D_i	e	PN
	mm			mwc
LDPE	10	9.554	1.156	30
	13	13.120	1.086	30
	16	16.818	0.951	30
	20	20.720	1.148	30
	26	27.241	1.587	40
PVC*	35	35.716	**	60
	50	47.564		80
	75	72.054		80

*Data obtained from Vilaça (2012); ** Data not available in the study of Vilaça (2012) estimated using the modified equation of Darcy-Weisbach (Eq. 2) (Rettore Neto et al., 2014), which considers the variation in the internal diameter of elastic pipes due to pressure effects. For rigid PVC pipes, the head loss was estimated using the conventional equation of Darcy-Weisbach, which was compared with the head loss obtained through hydraulic tests.

$$f = \left\{ \left(\frac{64}{Re}\right)^{1/p_1} + 1.325^{1/p_1} \left[\ln\left(\frac{\varepsilon}{3.7\ D} + \frac{5.74}{Re^{0.9}}\right) - \left(\frac{k_1}{Re}\right)^{P_2} \right]^{-2/p_1} \right\}^{p_1} \qquad (1)$$

$$hf = f \frac{L}{D/\left[1-\left(PD/eE\right)\right]} \frac{V^2}{2g} \qquad (2)$$

where:

f - friction factor, dimensionless;
ε - absolute roughness, m;
Re - Reynolds number, dimensionless;
p_1 = 0.125, k_1 = 2500 and P_2 = 6 - constants obtained experimentally;
D - internal diameter of the pipe, m;
hf - head loss, m;
L - pipe length, m;
V - flow velocity, m s^{-1};
g - gravity acceleration, m s^{-2};
P - pressure inside the pipe, MPa;
e - pipe wall thickness, m; and,
E - module of elasticity of the pipe material, MPa.

The relationship between flow rate and head loss in LDPE pipes was determined using a test bench illustrated in Figure 1. The test pressure was maintained at 196 kPa at the entry of the line and monitored using a digital manometer (measurement range from 0 to 500 kPa and expanded uncertainty of 0.26% in relation to the full scale).

Pressure gauge connections were installed at the beginning and at the end of the line, and the evaluated length was 21 m for the pipes of 13, 16, 20 and 26 mm, and 15 m for the pipe of 10 mm, because the head loss at the highest flow rates is greater than the available test pressure. Water temperature was monitored during the tests to obtain the kinematic viscosity, using a mercury thermometer with measurement range from 0 to 100 °C and expanded uncertainty of 1.08 °C. Flow rate readings were performed with an electromagnetic meter able to operate in the measurement range from 0 to 4 m^3 h^{-1}, with expanded uncertainty of 0.5% in relation to the full scale. 15 flow rates were tested with equidistant intervals, determined according to the criteria of Re ≥ 3000 and flow velocity not higher than 3 m s^{-1}. This range encompasses the limits of water flow velocity normally used in irrigation projects (Bernardo et al., 2006). A differential pressure transducer was used to measure the head loss (measurement range from 0 to 200 kPa, expanded uncertainty of 0.1% in relation to the full scale). The length for head loss evaluation in the LDPE pipes was measured with a tape measure, while the internal diameter and wall thickness were determined with a profile optical projector (model Starrett HB 400).

The results of head loss obtained by Vilaça (2012), in a study conducted in the same laboratory under similar test conditions, were used for PVC pipes.

The values of head loss obtained in the hydraulic tests were compared with the estimated ones, using the values of the parameters measured with the roughness meter in the calculation of the f factor. The parameter that best expresses roughness was selected based on the following indicators: Root Mean Square Error - RMSE (Willmott et al., 2012); 1:1 lines; and frequency distribution of the relative error between the estimates and observations of head loss, calculated according to Eq. 3.

$$RE_{(\%)} = \left|\frac{Pi - Oi}{Oi}\right| 100 \qquad (3)$$

where:

$RE_{(\%)}$ - relative error, %;
Pi - values predicted in head loss estimates, m; and,
Oi - values observed in head loss measurements, m.

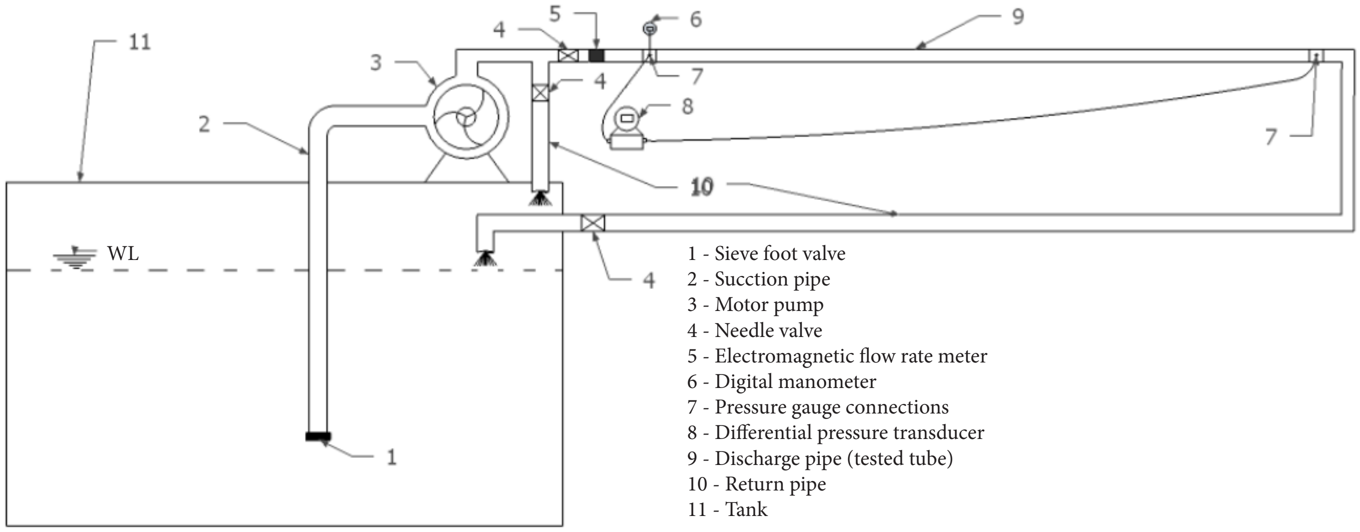

Figure 1. Structure used to conduct the tests for the determination of head loss in polyethylene pipes

Results and Discussion

The descriptive statistics of the parameters Ra, Rq, Rc and Ry, in longitudinal and transverse directions to the water flow in the pipe, for each diameter, is presented in Table 2, which shows the mean and dispersion of the data. The variability of roughness measurements was lower in PVC pipes (DN 35, 50 and 75), evidenced by the lower standard deviations. The parameters Ry and Rc are essentially more sensitive to the detection of greater amplitudes of the protrusions of the internal wall of the pipe (Farshad et al., 2001), while the parameters Ra and Rq constitute, by definition, a statistical representation of the points measured on the evaluated surface (Gadelmawla et al., 2002).

Faria et al. (2010) used a roughness meter with probe tip with 2.0 μm and 60° of radius and tip angle, respectively, and concluded that the device proved to be satisfactory to evaluate the mean roughness (Ra) of polyethylene pipes. However, these authors evaluated only the parameter Ra and not the others. Farshad et al. (2001) recommend the adoption of the parameter R_{ZD}, equivalent to Rc of the present study, to calculate the head loss in gas and oil pipelines, due to its capacity to detect protrusions more probable to affect the flow.

The exponents of the flow rate in the equations varied from 1.7327 to 1.8114, remaining between 1.7 and 2.0 for the mean velocity. Using the f calculated by the Blasius equation, associated with the Darcy-Weisbach equation, this exponent is equal to 1.75. The calculated values of head loss were obtained through the equation of Swamee (1993) for the friction factor f, with ε from the different roughness parameters measured. Based on the RMSE (Table 3), the continuous head loss can be influenced by the roughness parameter adopted in f estimation in each diameter evaluated, and the best fits were observed in pipes of 10 and 35 mm with the parameter Rq; 13 and 16 mm with the parameter Ry; 20, 50 and 75 mm with the parameter Rc; and 26 mm with the parameter Ra. The last column of the table illustrates the ranking of estimates made using the evaluated parameters, following an increasing order of RMSE.

For PVC pipes, there was a tendency of lower RMSE, which can be associated with three factors: previously fitted equations were used, which may have smoothed deviations previously observed in the data that originated these equations. The manufacturing processes of PVC pipes, in general, have superior quality and result in surfaces with lower variability and magnitude of roughness, while for low values of ε, the term relative roughness of the equation for f calculation becomes lower as the pipe diameter increases, influencing less the final value of head loss.

Table 3. Nominal diameter (DN), internal diameter (D_i), coefficients "a" and "b" of the flow rate-head loss curve and root mean square error (RMSE) of the estimates of continuous head loss in the pipes based on the roughness parameters

Parameter	DN	D_i	$hf = a\ Q^b$		Mean RMSE	Ranking
		mm	a	b	mm	RMSE
Ra	10	9.554	27.924	1.763	0.396	2
Rq					0.319	1
Ry					1.180	4
Rc					0.725	3
Ra	13	13.120	9.648	1.803	1.604	4
Rq					1.550	3
Ry					0.801	1
Rc					1.051	2
Ra	16	16.818	2.693	1.733	0.520	4
Rq					0.504	3
Ry					0.274	1
Rc					0.362	2
Ra	20	20.720	0.952	1.761	0.207	4
Rq					0.189	3
Ry					0.161	2
Rc					0.128	1
Ra	26	27.241	0.252	1.765	0.101	1
Rq					0.109	2
Ry					0.436	4
Rc					0.240	3
Ra	35*	35.716	0.057	1.755	0.032	2
Rq					0.027	1
Ry					0.094	4
Rc					0.039	3
Ra	50*	47.564	0.014	1.781	0.045	4
Rq					0.042	3
Ry					0.019	2
Rc					0.017	1
Ra	75*	72.054	0.002	1.811	0.012	3
Rq					0.010	2
Ry					0.021	4
Rc					0.005	1

*Data obtained from Vilaça (2012); hf: Head loss (mwc); Q: Flow rate ($m^3\ h^{-1}$)

The parameters Rc and Ry generated the worst results, while Rq led to the best estimates for LDPE pipes of 10 mm (Figures 2A and 2E). For 13 and 16 mm, Ry was the parameter with best fit and lower deviations of the observed head loss, while Rc and Ra led to the best estimates for 20 and 26 mm. In PVC pipes (Figures 2F to 2H), the best fits were observed with the parameters Rq for 35 mm and Rc for 50 and 75 mm of diameter.

The fitted 1:1 lines allow a better visualization of the condition of under- or overestimation generated by the use of the parameters measured in the roughness meter in the calculation of f, according to Swamee (1993), considering that the modified

Table 2. Descriptive statistics (Mean ± standard deviation) of the roughness parameters in each direction of scanning with the needle, for LDPE (DN 10 to 26 mm) and PVC (DN 35 to 75 mm) pipes

D	P	Nominal diameter - mm							
		10	13	16	20	26	35	50	75
Longitudinal	Ra	2.783 ± 0.970	2.131 ± 0.455	1.115 ± 0.291	1.561 ± 0.559	6.302 ± 0.959	1.349 ± 0.267	1.308 ± 0.157	1.282 ± 0.131
	Rq	3.611 ± 1.222	2.694 ± 0.617	1.453 ± 0.414	2.039 ± 0.758	7.799 ± 1.104	1.761 ± 0.326	1.617 ± 0.190	1.590 ± 0.156
	Ry	16.580 ± 5.127	12.480 ± 3.084	7.170 ± 2.183	10.050 ± 3.804	36.020 ± 4.508	8.731 ± 1.638	7.247 ± 0.835	7.263 ± 0.627
	Rc	11.040 ± 3.670	8.371 ± 2.551	4.453 ± 1.726	6.381 ± 3.122	22.360 ± 3.901	4.740 ± 0.917	4.458 ± 0.627	4.180 ± 0.548
Radial	Ra	4.651 ± 1.300	3.288 ± 1.256	1.644 ± 0.542	2.838 ± 0.970	5.119 ± 0.721	1.353 ± 0.203	1.213 ± 0.202	1.166 ± 0.177
	Rq	5.886 ± 1.557	4.085 ± 1.600	2.057 ± 0.648	3.592 ± 1.386	6.244 ± 0.785	1.761 ± 0.242	1.484 ± 0.256	1.425 ± 0.199
	Ry	23.800 ± 6.027	15.920 ± 5.756	7.893 ± 2.137	12.530 ± 6.377	23.750 ± 3.183	9.193 ± 1.380	6.126 ± 0.928	6.296 ± 0.693
	Rc	18.210 ± 5.830	12.210 ± 5.324	6.110 ± 1.583	10.400 ± 2.508	17.660 ± 3.144	5.370 ± 1.21	4.021 ± 0.905	3.820 ± 0.607

P - Parameter

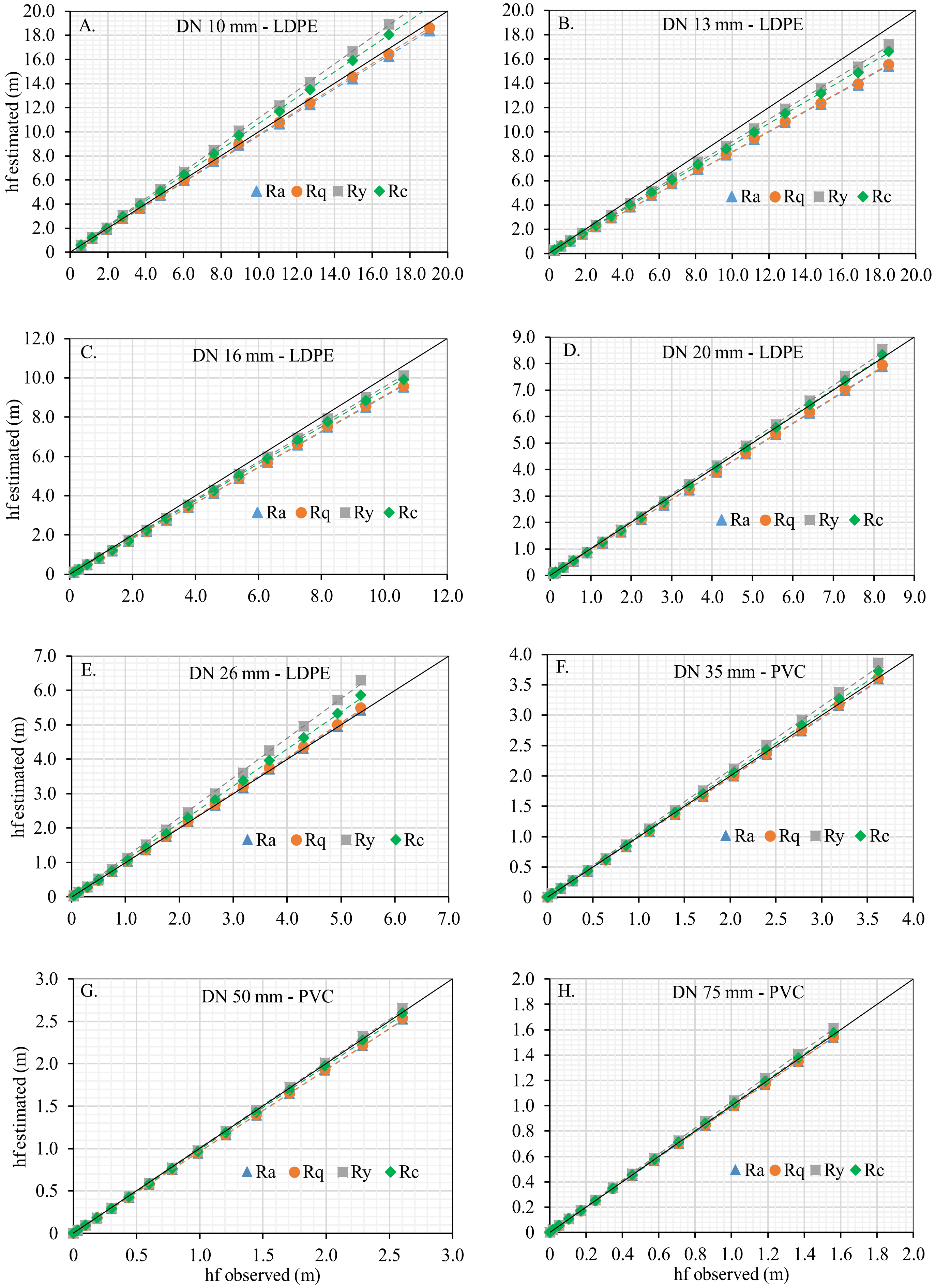

Figure 2. 1:1 lines for the estimates of continuous head loss (hf) through the parameters Ra, Rq, Ry and Rc for the evaluated diameters of polyvinyl chloride (PVC) and low-density polyethylene (LDPE)

equation of Darcy-Weisbach (Rettore Neto et al., 2014) was used for LDPE and Darcy-Weisbach for PVC in the estimates of head loss. The roughness equivalent to the sand grain originally defined in the studies of Johann Nikuradse (Hager & Liiv, 2008; Yang & Jooseph, 2009) was satisfactorily correlated with the parameters Ra, Rq and Rc by Afzal et al. (2013), evaluating turbulent flow in rough pipes.

Figure 3 shows the analysis of frequency distribution of relative errors of the head loss estimates adopting the best roughness parameter, identified by the ranking in Table 3. In general, higher and more frequent errors were observed for LDPE pipes.

It was observed, for example, that only 7.5% of the data showed error higher than 4.27, 3.62 and 4.93% in pipes of 35, 50 and 75 mm, respectively, with maximum relative error of 12.32% for 75 mm in 0.83% of the data, with f of Swamee (1993) calculated using the parameter Rc. However, errors higher than 10% occur at higher frequency for LDPE, with the respective chances of occurrence of 1.50, 28.17, 16.25, 5.09 and 8.69% for pipes of 10, 13, 16, 20 and 26 mm, respectively, considering the use of the parameters Rq for 10 mm, Ry for 13 and 16 mm, Rc for 20 and Ra for 26 mm. In this analysis, priority was given to the use of the parameter that resulted in lower RMSE value in each diameter, considered as superior to the others and more precise in f calculation for subsequent estimation of continuous head loss, after the evaluation of the statistical performance indicator RMSE.

Based on the presented analyses and considering the means of the parameters that resulted in better statistical performance of the head loss estimates, the mean values of internal surface roughness of 3.334 and 8.116 µm are suggested for PVC and LDPE, respectively, both contained in the wide general range recommended in tables (1.5 µm ≤ ε ≤ 10 µm) (Porto, 2006; Bernardo et al., 2006). Some authors observed reduction of the friction factor in plastic pipes and attribute the fact, besides other reasons, to the decrease in the roughness of the internal walls of the current commercial pipes (Bagarello et al., 1995; Cardoso & Frizzone, 2008).

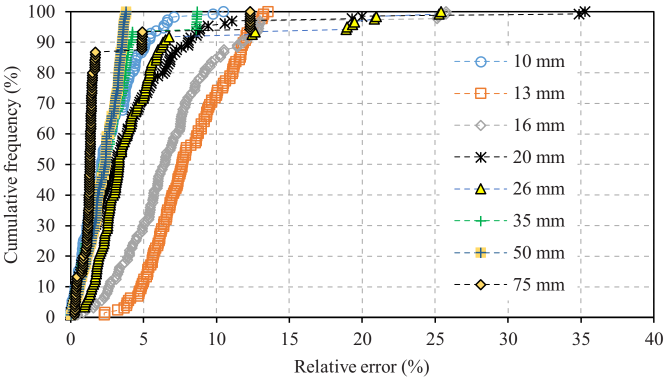

Figure 3. Frequency distribution of the relative error ($ER_{(\%)}$) in head loss estimates

CONCLUSIONS

1. There was difference in the use of the parameters Ra, Rq, Rc and Ry to represent the roughness of PVC and LDPE pipes and, therefore, it is proposed that the adoption of values and parameters of roughness specific for each diameter contributes to the accuracy of head loss estimates.

2. The results of the present study allow to recommend mean values of roughness of the internal walls of 3.334 and 8.116 µm for PVC and LDPE, respectively, which are within the wide general range recommended in tables (1.5 µm ≤ ε ≤ 10 µm).

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