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Methodology for designing lateral lines with microtubes operated under variable inlet pressure

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ABSTRACT

Design of lateral lines consisting of microtubes enables to optimize water distribution uniformity. In addition, there must exist a range of pressures at the lateral line inlet in which the water distribution uniformity remains acceptable. Thus, such emitters are interesting for use in micro-irrigation systems supplied by alternative power sources, in which temporal variability in the electrical power supplied to the pumping systems normally occurs. This study presents a methodology for designing lateral lines with microtubes operated under varying pressure, using the step-by-step method in order to establish the recommended range of lateral line inlet pressures. The proposed methodology was validated over three replicates by testing maximum, minimum and optimum pressures. Deviation between estimated and observed values of flow rate was lower than 6%, indicating a satisfactory accuracy. Distribution uniformity of the system was higher than 95% under all pressures within the estimated range of values. Lateral lines can operate within a wide range of operating pressures and even so satisfactory results of distribution uniformity are obtained.

Palavras-chave:

microirrigação
energia alternativa
uniformidade de distribuição

Metodologia para dimensionamento de linhas laterais com microtubos operadas sob pressão de entrada variável

RESUMO

O dimensionamento de linhas laterais constituídas por microtubos de comprimento variável, permite a obtenção de uniformidade de distribuição de água otimizada. Supõe-se que existe um intervalo de pressões de entrada na linha lateral no qual a uniformidade de distribuição de água é mantida dentro de limites aceitáveis. Deste modo, esses emissores podem ser aplicados em sistemas de irrigação em que há variação temporal de potência para o bombeamento. Assim, este trabalho propõe uma metodologia para dimensionar linhas laterais constituídas por microtubos sob pressão variável utilizando o método trecho a trecho a fim de se estabelecer o intervalo de pressões recomendadas para operação. A metodologia foi validada ensaiando-se a pressão máxima, ótima e mínima obtida, com três repetições. A diferença entre valores estimados e observados de vazão foi inferior a 6%, indicando que o equacionamento adotado apresentou acurácia satisfatória. A uniformidade de distribuição do sistema foi superior a 95% para todas as pressões ensaiadas; demonstrou-se, portanto, que é possível estabelecer um amplo intervalo de pressões de operação mantendo-se a uniformidade de distribuição dentro de limites aceitáveis.



INTRODUCTION

Microtubes are long-distance emitters whose length can be adjusted according to the distribution of pressures along the lateral line (Almeida et al., 2009), allowing optimized distribution uniformity. The flexibility for the configuration of each microtube in lateral lines becomes interesting for use in irrigation systems operated with alternative power sources, such as solar or aeolian. These power sources have temporal variability in the electric power supplied to motor pump set, and it is common to use power accumulators, tanks, pressure-compensating emitters (Pande et al., 2003) and/or pressure-regulating valves, for the flow rate to remain stable during the irrigation events. However, these devices exhibit losses that could be reduced in case of direct attachment between the irrigation system and the motor pump set; for that, it is convenient that the irrigation systems accept certain variations of power.

Studies on the uniformity of irrigation systems operated under different pressures (Chigerwe et al., 2004; Almeida et al., 2006; Sah et al., 2010; Klein et al., 2013) and on the use of alternative power sources directly attached to the irrigation systems are available in the literature (López-Luque et al., 2015; Reca et al., 2016). However, little is known about the range of inlet pressures that guarantees adequate distribution uniformity. It is imagined that, in the utilization of microtube emitters, there is a range of inlet pressures in the line, around an optimal value that allows operation with proper distribution uniformity and, therefore, it is admissible that there are variations in the inlet pressure of lateral lines.

Thus, the objective of this study was to develop a methodology for the dimensioning of lateral lines with microtubes operated under variable inlet pressure, determining the limits according to the environmental conditions.

MATERIAL AND METHODS

Methodology of dimensioning

The methodology proposed for the dimensioning of lateral lines, consisting of microtube emitters operated under variable inlet pressure, is characterized by the steps described hereinafter. For microtube length and diameter, defined according to characteristics of the project or availability of material, one must calculate the pressure necessary at the inlet of the last emitter of the lateral line to obtain a pre-defined flow rate (Eq. 1). The Eq. 1, adapted from Souza & Botrel (2004), is valid for microtubes operating in the laminar flow regime and contains terms that allow to quantify the head loss distributed along the microtube, the local loss resulting from the narrowing of the flow lines at the microtube inlet hole, the kinetic head on the discharge end of the microtube and the vertical distance between the microtube discharge hole and the lateral line.

$$H = \frac{64}{RN} \frac{L}{D} \frac{v^2}{2g} + k \frac{v^2}{2g} + \frac{v^2}{2g} \pm Z \quad (1)$$

where:

- H - head at the microtube inlet;
- RN - Reynolds number, dimensionless;

- L - microtube length, m;
- v - mean water flow velocity in the microtube, $m s^{-1}$;
- D - microtube internal diameter, m;
- g - gravity acceleration, $m s^{-2}$;
- k - local head loss coefficient, dimensionless; and,
- Z - gradient between the microtube discharge hole and the lateral line, m.

Once the required head at the last emitter of the lateral line is determined, the lateral line is dimensioned through the step-by-step method, with calculation from the last emitter (Yildirim, 2010). The procedure consists in the calculation of the pressure at the emitter $i-1$ considering the pressure at the emitter i , the losses distributed in the segment between both emitters considered and the local head losses at the emitter $i-1$ (Eq. 2). The index i represents the emitter closest to the end of the lateral line, while $i-1$ indicates the emitter immediately after the emitter i . Once the pressure at $i-1$ is determined by Eq. 2, the microtube length at $i-1$ is determined by Eq. 1. The procedure is repeated until all microtubes of the lateral line are dimensioned.

$$H_{i-1} = H_i + hf_{D_{i \rightarrow (i-1)}} + hf_{L_{(i-1)}} \quad (2)$$

where:

- H_{i-1} - head at emitter $i-1$, m;
- H_i - head at emitter i , m;
- $hf_{D_{i \rightarrow (i-1)}}$ - head loss distributed along the segment between both emitters in question, m; and,
- $hf_{L_{(i-1)}}$ - local head loss in the lateral line due to the insertion of the emitter $i-1$, m.

After dimensioning the length of all microtubes, the inlet pressure of the line (H_0) is calculated, which results from the sum of the pressure in the first emitter with the total head loss in the segment between this emitter and the beginning of the line. The obtained value represents the optimal pressure (P_{opt}) because, theoretically, it provides a flow rate variation (Q_{var}) of 0% (Eq. 3).

$$Q_{var} = 100 \frac{(Q_{max} - Q_{min})}{Q_{max}} \quad (3)$$

where:

- Q_{var} - flow rate variation, %;
- Q_{max} - highest flow rate, $L h^{-1}$; and,
- Q_{min} - lowest flow rate, $L h^{-1}$.

Subsequently, the admissible range of inlet pressures is determined, in which the distribution uniformity of the lateral line remains within acceptable limits of the order of 10 to 20% (Frizonne et al., 2012). After defining the flow rate variation accepted in the already dimensioned lateral line, the admissible range of pressures is calculated through iterations. The maximum pressure (P_{max}) at the inlet of the lateral line is obtained through increments in the pressure of the last emitter, recalculating the pressure and flow rate profiles and then the value of Q_{var} in the lateral line. The maximum

admissible pressure is that resulting in Q_{var} close to the value pre-established as criterion for hydraulic dimensioning of the lateral line. Similarly, the minimum pressure (P_{min}) at the inlet of the lateral line is obtained through iterations, decreasing the pressure of the last emitter until reaching Q_{var} close to the pre-defined value.

Demonstration of use of the methodology

To demonstrate the proposed methodology, the following conditions were established for the dimensioning of one lateral line, which was projected and installed at the field: a) level lateral line, constituted by a polyethylene pipe with internal diameter of 12.7 mm; b) vertical distance of 13 cm between the lateral line and the microtube discharge hole; c) line with 240 microtubes spaced by 10 cm, which should have flow rate of 1.0 L h⁻¹ when operated at the optimal pressure (31.97 kPa); d) microtubes with internal diameter of 0.739 mm; e) local head loss coefficient due to the narrowing of the flow lines at the microtube inlet hole (k) equal to 17.78; f) local head loss in the lateral line due to the insertion of the microtube estimated by $hf_1 = 0.01239 v^{1.543}$, for the laminar flow regime; and by $hf_1 = 0.00660 v^{1.679}$, for the other flow regimes; g) admissible flow rate variation in the lateral line (Q_{var}) defined as 7%; h) water temperature of 25 °C; i) increments of 9.81 Pa in the iterative calculations for the determination of P_{min} and P_{max} .

In segments of the lateral line with laminar flow regime (RN < 2000), the friction factor (f) of the Darcy-Weisbach equation was calculated using Eq. 4. For the rest of the flow conditions (RN ≥ 2000), Eq. 5 was used and its coefficients were adjusted to polyethylene pipes with small diameter (Cardoso et al., 2008).

$$f = \frac{64}{RN} \tag{4}$$

$$f = \frac{0.3}{RN^{0.25}} \tag{5}$$

where:

RN - Reynolds number, dimensionless.

Indicators of uniformity in the lateral line

The previously dimensioned line was evaluated at the field in 2014, operating under optimal pressure and at the calculated upper and lower limits. For that, the flow rates of 51 emitters were measured along the line and compared with the estimated results. The flow rate was determined based on the mass of water collected in a time sufficient to collect approximately 400 to 500 g. Three replicates were performed for the three pre-determined pressures for water temperature in the test, which was 20 °C. Water temperature was used to determine the specific weight of water through the equation suggested by Kell (1975) (Eq. 6).

$$\rho = \frac{\left(999.8676 + 17.801161T - 7.942501 \times 10^{-3} T^2 - 52.56328 \times 10^{-6} T^3 + 137.6891 \times 10^{-9} T^4 - 364.4647 \times 10^{-12} T^5 \right)}{\left(1 + 17.735441 \times 10^{-3} T \right)} \tag{6}$$

where:

- ρ - specific weight of water, kg m⁻³; and,
- T - temperature, °C.

Values observed at the field and mathematically estimated were compared through the relative difference of flow rate (Eq. 7), obtained for each emitter evaluated, at each pressure.

$$\Delta Q = 100 \left(\frac{\left| \overline{q_o} - \overline{q_e} \right|}{\overline{q_o}} \right) \tag{7}$$

where:

- ΔQ - relative difference, %;
- $\overline{q_o}$ - mean flow rate observed, L h⁻¹; and,
- $\overline{q_e}$ - mean flow rate estimated, L h⁻¹.

Distribution uniformity was expressed through the statistical uniformity coefficient (SUC) and distribution uniformity of the lowest quartile (DU).

Lastly, due to the sensitivity of the microtube flow rate to water temperature, especially for laminar flow regime, P_{opt} , P_{max} and P_{min} were calculated for the temperatures of 10, 15, 20, 25, 30 and 35 °C, where P_{opt} is the pressure that would lead to the lowest Q_{var} .

RESULTS AND DISCUSSION

As shown in Figure 1A, the length of the microtubes installed in the lateral line used as example decreased from the first to the last emitter, since the pressure decreased along the line due to the head loss. Thus, the first emitters are longer, to dissipate more pressure at the beginning of the lateral line and, consequently, provide the pre-established flow rate. Although the flow rate was maintained constant along the lateral line, the dimensioning requires each microtube to have individualized length (Figure 1A).

Regarding the inlet pressure of the projected lateral line, the optimal value (P_{opt}) was 31.97 kPa, whose pressure at the end of the line was 26.15 kPa (Figure 1B), leading to a Q_{var} equal to 0, despite a pressure variation of approximately 18%. In the case of emitters with flow exponent equal to 0.5, this same pressure variation would lead to Q_{var} of approximately 10%, indicating that, despite the labor required to build the lateral lines, in systems with variable pressure the use of microtubes has, as advantage over emitters with turbulent flow, the generation of longer lateral lines with no losses in terms of flow rate variation or distribution uniformity.

Respecting the maximum flow rate variation of 7% between the first and last emitters of the lateral line, the inlet pressures can vary between 13.28 kPa (P_{min}) and 68.64 kPa (P_{max}). Hence, it is possible to alter the inlet flow rate to values within this interval, promoting flexibility in the operation of the lateral lines and maintaining the flow rate variation within the stipulated limit.

Due to the alteration in microtube flow rate because of water temperature, the pressure limits must be corrected. Figure 2 presents these relationships, as well as the intervals

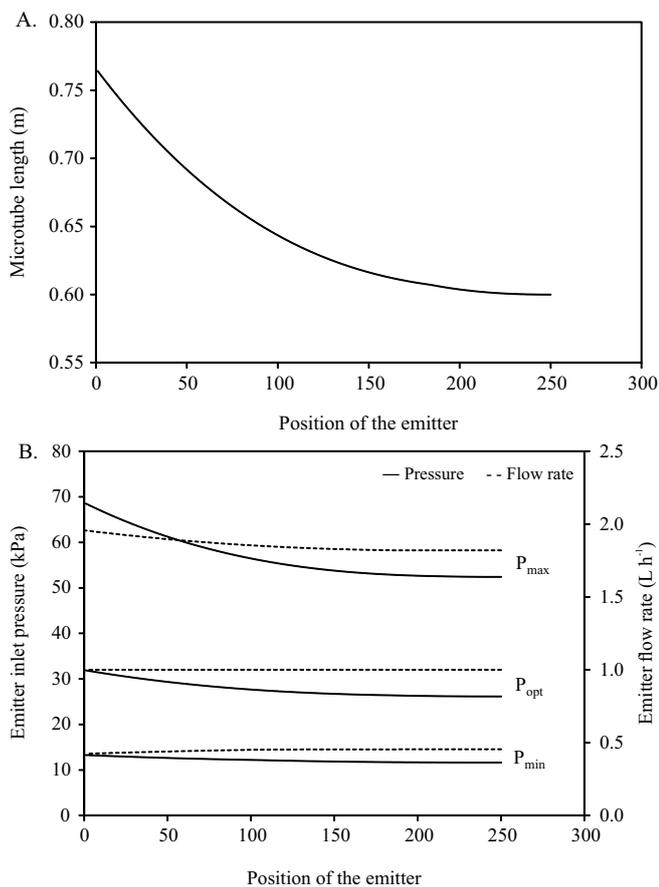


Figure 1. Variation of microtube length along the projected lateral line (A); Profiles of minimum, optimal and maximum pressures along the projected lateral line (B) considering water temperature of 25 °C

recommended for the operation of the lines, according to the water temperature (from 10 to 35 °C). The values of inlet pressure (Figure 2A) and mean flow rate of the emitters (Figure 2B) were also obtained respecting the criterion of 7% of flow rate variation along the lateral line. As water temperature decreased, the range of inlet pressure increased, allowing greater flexibility for operation. While for the temperature of 10 °C, P_{min} was 29.02 kPa and P_{max} was 150.48 kPa, for the temperature of 35 °C, P_{min} and P_{max} were equal to 8.24 and 43.06 kPa, respectively. Thus, for each one of these temperatures there may be a modification of more than five times in the inlet pressure of the line and, despite that, the distribution uniformity is maintained within acceptable limits. In addition, since the variation in water temperature leads to variation of inlet pressure in the line, there is also a change in the flow rate of the emitters (Figure 2B).

The water temperature for which the field test was conducted was 20 °C, requiring the calculation of the

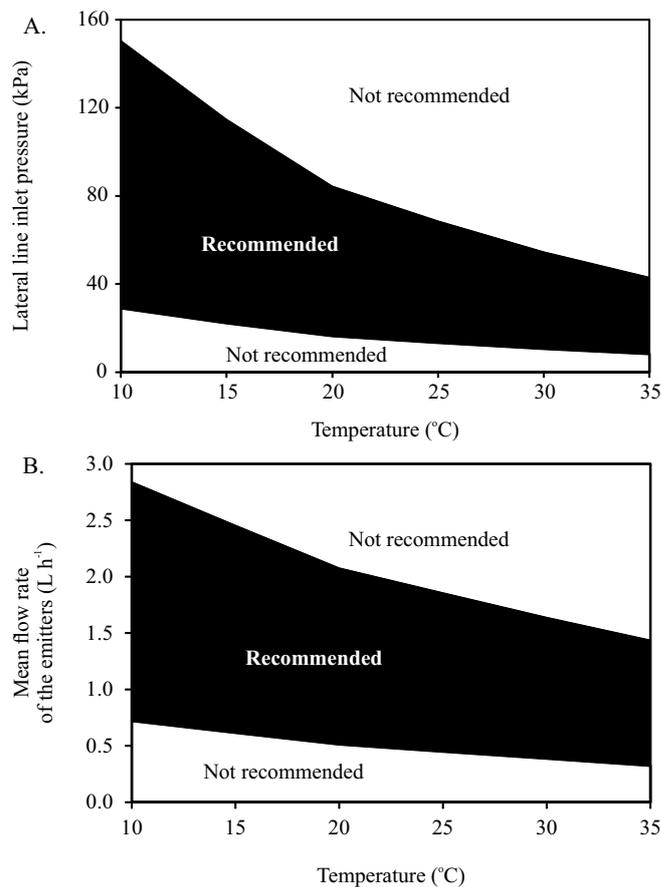


Figure 2. Effect of water temperature on the acceptable limits of lateral line inlet pressure (A) and on the mean flow rate of the microtube emitters (B)

corresponding pressures. The results of this analysis are presented in Table 1.

Both indices, DU and SUC, reported excellent uniformity according to Bralts (1986), since they were all above 90%. These results of uniformity, along with the values of relative difference of flow rate, indicate that the dimensioning of the range of pressures was valid under the conditions of the experiment and for the established criteria. Also testing different operating pressures in microtube kits, Sah et al. (2010) obtained DU values above 90% and SUC higher than 85%, both for the conditions of level and non-level line. The obtained results of SUC are consistent with those of Souza et al. (2011), who also obtained excellent values (98.25%) using microtubes with variable lengths in fertigation. This indicates that microtubes with different lengths along the line have more advantage over those with a single length, although Souza et al. (2006) report DU values of 96.9% for microtubes with fixed length. In evaluations of kits of lines with fixed-length microtubes, Chigerwe et al. (2004) also varied the inlet pressure, but the mean values of DU were lower

Table 1. Information on the operation of the lateral line, relative differences of flow rates and indicators of distribution uniformity for the three tested pressures

Pressure	Pressure (kPa)	Mean flow rate of the emitters (L h ⁻¹)		Relative difference between estimated and observed flow rates (%)	DU*	SUC*
		Estimated	Observed			
P _{min}	16.32	0.51	0.50	1.77	95.25	96.79
P _{opt}	39.00	1.12	1.11	0.56	97.80	98.37
P _{max}	84.43	2.08	2.06	1.12	97.93	98.37

* DU - Distribution uniformity of the lowest quartile; SUC - Statistical uniformity coefficient

than 90% in three of the four kits. Souza et al. (2009) evaluated similar kits and obtained DU values lower than 70% in some of them, which can be considered as bad (Bralts, 1986), agreeing that the utilization of emitters with the same length was one of the factors for the lower uniformity.

The first emitters showed greater differences between estimated and observed flow rate (Figure 3A). Anyway, the highest value of ΔQ obtained was approximately 6%, for P_{max} , which indicates that the hydraulic estimates were sufficiently accurate and adequately represent the evaluated system.

According to Figure 3B, approximately 90% of the ΔQ values (Eq. 7) were lower than 3%. For that, the strategy of compensating the flow rate along the line by modifying the length of the microtubes was validated with the experimental data; therefore, electrical energy sources with variable power supply can be used provided that the irrigation system operates within the admissible range of pressures calculated according to the described methodology. Hence, uniformity indices will be maintained adequate, even when the irrigation system operates under variable pressure.

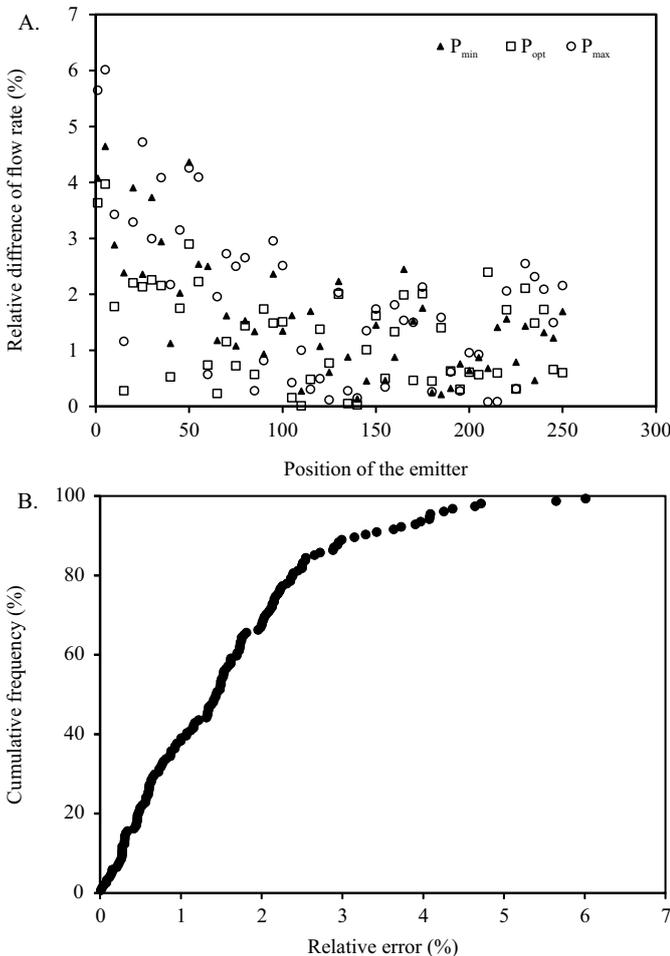


Figure 3. Relative differences of flow rate in the emitters for the maximum (P_{max}), optimal (P_{opt}) and minimum pressure (P_{min}) (A); cumulative frequency of the errors between observed and estimated values (B)

CONCLUSIONS

1. The utilized methodology allows to dimension lateral lines constituted by microtubes with variable length.

2. The utilized methodology allows to determine the range of operating pressures that guarantees adequate distribution uniformity.

3. The deviations between flow rate values observed at the field and estimated were lower than 6%, indicating adequate accuracy of the equating adopted in the dimensioning.

4. Water temperature has significant influence on the recommended range of operating pressures of lateral lines that use microtube emitters.

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