

Minor losses in start connectors of microirrigation laterals

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Received: 27 January 2016 / Accepted: 30 January 2017 / Published online: 2 March 2017
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Abstract Fittings called start connectors are usually employed to attach each lateral to its corresponding manifold in microirrigation systems. The protrusion of start connectors' barbs into the manifold induces pressure losses due to contraction and subsequent enlargement of streamlines. In addition, when water flows from a manifold toward a lateral through a start connector, a sudden contraction followed by expansions of flow streamlines cause pressure loss whose intensity is influenced by connector's geometry. Minor losses along manifolds or at laterals inlet due to start connectors may be significant and might be considered on subunits design or while undertaking hydraulic simulations. The objectives of this research were: (a) to develop equations based on dimensional analysis to estimate minor losses due to start connectors; (b) to compare the accuracy of the developed models against models that are currently used for estimating minor losses; (c) to undertake simulations to assess the relevance of minor losses due to start

connectors in hydraulics of subunits. Minor losses due to start connectors were separated into two components. A model was developed and validated to estimate minor losses due to the protrusion of start connectors inserted along a manifold. Two models were developed and validated to estimate minor losses that occur when water flows from a manifold into a lateral line through a start connector. The required data to develop and validate the models were obtained experimentally in laboratory. Although minor losses due to start connectors represented a relative small percentage of total head losses, such effects may be significant while undertaking rigorous hydraulic simulations that require accurate estimation of pressure losses.

Keywords Head loss · Dimensional analysis · Buckingham Pi theorem

Introduction

In microirrigation systems, water is delivered near the root zones of crops by emitters installed on polyethylene pipes called laterals. Within irrigation subunits, water is conveyed from manifolds toward laterals. Design of microirrigation subunits is based on water distribution uniformity criteria and requires accurate estimation of total energy losses that accounts for friction losses along pipes and local pressure losses or minor losses (Yildirim 2007). In a subunit, the water distribution uniformity relies on emitters flow rate that is affected by the available pressure head at emitter's inlet, when non-pressure-compensating emitters are used. The pressure head varies along manifold and laterals mainly due to pressure losses, slight differences in emitters' geometry due to manufacturing imperfections, emitters' clogging and

Communicated by J. Hornbuckle.

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pressure variations caused by slope (Provenzano and Pumo 2004; Perboni et al. 2015).

Although minor losses are often neglected, previous studies had demonstrated their importance while designing microirrigation systems (Al-Amoud 1995; Bagarello et al. 1997; Juana et al. 2002a, b; Provenzano and Pumo 2004; Yildirim 2007, 2010; Rettore Neto et al. 2009b). Minor losses due to protrusion of online emitters barbs into polyethylene pipes of 13 and 25 mm represented an increase from 5 to 32% in the total energy losses (Al-Amoud 1995). It was also reported that neglecting the effect of minor losses may lead to errors of 25% in design diameters and 7% in laterals maximum length (Yildirim 2007). Local head losses contributed between from 6.4 and 49.5% of total energy losses in simulations for designing laterals considering two models of pipes with integrated coextruded emitters (Provenzano and Pumo 2004). In another study, total head loss increased from 24.5 to 50.8% due to minor losses caused by non-coaxial drippers integrated to polyethylene pipes (Rettore Neto et al. 2009a).

Previous experimental investigations determined a relationship (Eq. 1) for estimating minor losses along pipes consisting of online emitters (Bagarello et al. 1997). Equation 1 is determined based on experiments with six models of online emitters attached to polyethylene (PE) pipes of 16 and 20 mm diameter. Reynolds number varied from 3971 to 22,171 during the experiments. According to the authors, for a given setup of emitter and PE pipe, α can be assumed independent of the Reynolds number for values higher than 10,000.

$$h_{f_L} = \alpha \frac{V^2}{2g} = 1.68 \left(\frac{A}{A_r} - 1 \right)^{1.29} \frac{V^2}{2g} \tag{1}$$

where: h_{f_L} is the local head loss due to protrusion of one emitter; α is a coefficient of local head loss; A is the pipe cross-sectional area; A_r is the flow cross-sectional area where the emitter is located; V is the mean flow velocity along the pipe; and g is the gravitational acceleration.

Similarly, for drip-lines with coextruded emitters, the local head losses were estimated by Eq. 2 (Provenzano and Pumo 2004). Equation 2 is fitted based on experimental data from ten drip-line models of geometrical characteristics within the range of $1.00 < \frac{A}{A_r} < 1.44$, that were tested under Reynolds number varying from 2314 to 24,321. Average values of α varied from 0.102 to 1.194. For a given model of drip-line, α values were considered independent of the Reynolds number for values higher than 5000.

$$h_{f_L} = 0.056 \left[\left(\frac{A}{A_r} \right)^{8.915} - 1 \right] \frac{V^2}{2g} \tag{2}$$

Usually, fittings called start connectors are employed to attach each lateral to its corresponding manifold. The protrusion of start connectors' barbs into the manifold presents

a hydraulic behavior similar to that of online emitters attached to laterals, since both cause contraction and subsequent enlargement of streamlines resulting in minor losses along pipes.

Start connectors are also associated with a component of local head loss that may affect the design of lateral lines. When water flows from a manifold toward a lateral, there is a sudden contraction followed by one or more expansions of flow streamlines that varies according to connector's geometry. The behavior of start connectors operating in the mentioned condition is quite similar to connectors used in microsprinkler systems for attaching microtubes into PE pipes in order to convey water from the lateral to a microsprinkler. Zitterell et al. (2013) developed an equation based on dimensional analysis to estimate local head loss that occurs when water flows through small connectors employed to attach one pipe to another (e.g., a polyethylene pipe to a microtube) (Eq. 3). The equation assumes a kinematic viscosity of $1.10 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ and $g = 9.81 \text{ m s}^{-2}$.

$$h_{f_L} = \frac{0.000143 D_{c_{out}}^{2.16} L_c^{0.92} D_L^{1.75} V_L^2}{D_{c_{in}}^{5.74}} \tag{3}$$

where: $D_{c_{in}}$ and $D_{c_{out}}$ correspond to the inlet and outlet diameters of the connector (m); L_c is the connector length (m); D_L is the diameter of the pipe attached to the connector outlet (m); V_L is the flow velocity at the pipe attached to the connector outlet (m s^{-1}). Equation 3 is valid for: $2.3 \leq D_{c_{in}} \leq 7.9 \text{ mm}$; $2.3 \leq D_{c_{out}} \leq 12.0 \text{ mm}$; $21.5 \leq L_c \leq 65.0 \text{ mm}$; $4.1 \leq D_L \leq 12.9 \text{ mm}$; $0.36 \leq V_L \leq 7.58 \text{ m s}^{-1}$; $3000 \leq Re \leq 66,000$.

Start connectors present larger protrusion areas than online emitters or connectors installed along laterals. Thus, Eq. 1 may not provide accurate estimation of minor losses caused by start connectors installed along manifolds. Likewise, Eq. 3 is not validated for dimensions and operating conditions related to start connectors; hence, such equation may not provide accurate results either. The pressure losses along manifolds or at laterals' inlet caused by start connectors may be significant and might be considered while designing subunits or while simulating its operational hydraulic conditions. None of the reported literature has described equations valid for the estimation of minor losses caused by start connectors commercially available. The objectives of this research were: (a) to develop equations based on dimensional analysis to estimate minor losses due to start connectors; (b) to compare the accuracy of the developed models against models that are currently used for estimating minor losses; (c) to undertake simulations to assess the relevance of minor losses due to start connectors in hydraulics of subunits. Minor losses due to start connectors were separated into two components. A model was developed and validated to estimate minor losses due

to the protrusion of start connectors inserted along a manifold. Two models were developed and validated to estimate minor losses that occur when water flows from a manifold into a lateral line through a start connector. The required data to develop and validate the models were obtained experimentally in laboratory.

Methodology

Laboratory tests

Minor losses along the manifold

The first stage of experiments aimed to collect data required to estimate minor losses caused by start connectors installed along a manifold. Friction head losses were determined by measuring the differential pressure in segments of PVC pipes of 15-m length without start connectors. Next, 15 start connectors were inserted along the segments of PVC pipes in distances of 1 m in order to measure the total head losses. The pipes were laid horizontally, and the start connectors were plugged to avoid reduction of flow rate along the PVC pipe (i.e., manifold). Minor losses were calculated based on the difference between total head losses and friction head losses. The measurements of pressure loss taking into account more than a single connector aimed to allow for a measurable amount of energy loss and to improve the reliability of results.

Experiments were undertaken in a testing bench consisting of a water tank, pump, electromagnetic flow meter (expanded uncertainty $\leq 0.5\%$), manometer (expanded uncertainty $\leq 0.25\%$), differential mercury manometer (resolution = 1 mmHg = 0.133 kPa), valves and samples of pipes under test (Fig. 1). The testing pressure was 200 ± 1 kPa. The water temperature during the experiments was 27 ± 1 °C.

Five models of start connectors (Table 1) were combined with PVC manifolds of 35, 50 and 75 mm (nominal diameter). The selected start connectors represent a variety

of common models of connectors commercially available. The diameters of PVC pipes also are practical sizes used in manifolds of microirrigation systems. Connectors 1 and 4 have inlet sections slightly smaller than their outlet so that they are geometrically similar (i.e., the connectors are slightly conical). Connector 2 has a gradual expansion, and connector 3 has a sudden expansion from inlet to outlet sections. Finally, connector 5 has an outlet section a little smaller than its inlet.

A horizontal benchtop optical comparator Starret HB400 was used for measuring the internal diameters of the start connectors; a digital caliper was used for measuring their length; and the protrusion area (A_g) was determined based on images (i.e., photographs) analyzed using CAD software (Fig. 2). Data shown in Table 1 are based on measurements of ten samples.

The internal diameter of ten samples of PVC pipes (manifold) of each nominal diameter was measured by a digital caliper (resolution 0.01 mm). The nominal diameters 35, 50 and 75 presented the following internal diameters (average value \pm standard deviation): 35.72 ± 0.11 ; 47.56 ± 0.12 ; and 72.05 ± 0.04 mm.

Minor losses at the lateral inlet

The second stage of experiments aimed to collect data required to estimate minor losses that occur when water flows from a manifold to a lateral through a start connector. Friction head losses were determined by measuring the differential pressure in segments of PE pipes of 21-m length without start connectors. Thereafter, each segment of PE pipe (lateral line) was attached to a PVC pipe (manifold) using a start connector. Total head losses were measured by installing pressure taps at the end of PE pipe and in the manifold, at the position where the start connector was attached to the manifold (Fig. 3). Local head losses were calculated based on the difference between total head losses and friction head losses. The measurements of pressure loss on 21-m length laterals aimed to allow for a

Fig. 1 Sketch of the testing bench used for measuring pressure losses caused by start connectors installed along a manifold: 1 water tank; 2 pump; 3 flow meter; 4 manometer; 5 differential mercury manometer; 6 pipe under test; 7 valve; 8 pipe for returning water to the tank

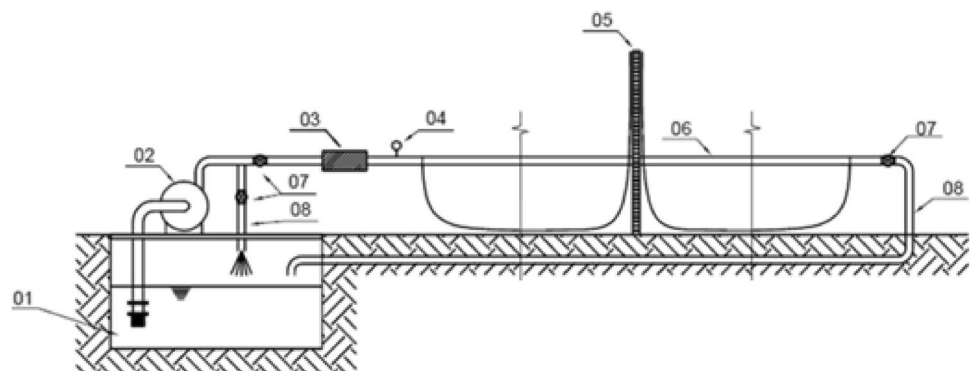


Table 1 Geometrical characteristics of the start connectors: internal diameter at the connector inlet (D_{cin}), internal diameter at the connector outlet (D_{cout}), connector length (L_c), protrusion area (A_g)

Start connector	Picture	D_{cin} (mm)	D_{cout} (mm)	L_c (mm)	A_g (mm ²)
1		7.001 ±0.107	7.765 ±0.048	58.07 ±0.64	104.105 ±6.963
2		7.086 ±0.026	11.290 ±0.031	49.55 ±0.21	148.416 ±6.229
3		8.676 ±0.028	16.741 ±0.041	66.44 ±0.06	156.514 ±6.422
4		9.833 ±0.053	11.255 ±0.106	50.23 ±0.23	210.556 ±7.743
5		16.051 ±0.945	15.400 ±0.044	52.31 ±0.11	345.453 ±1.373

Average value ± standard deviation

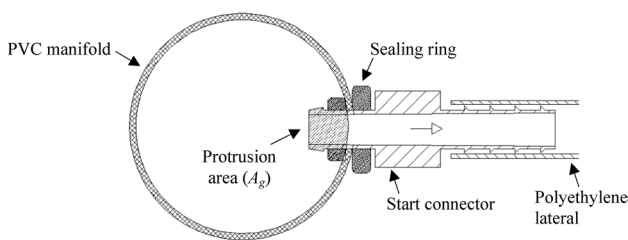


Fig. 2 Sketch illustrating the protrusion area of a start connector attached to a PVC pipe (manifold)

measurable amount of energy loss and to improve the reliability of results.

The same models of start connectors and PVC manifolds described previously were combined with polyethylene

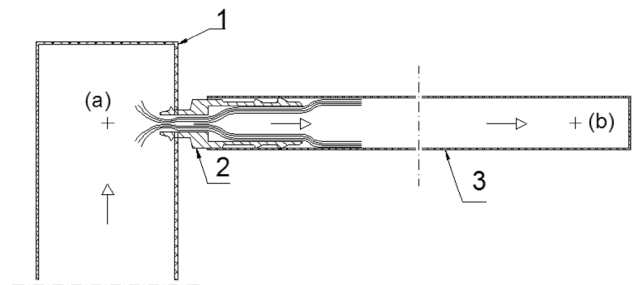


Fig. 3 Sketch illustrating a lateral line (3) attached to a manifold (1) using a start connector (2); a and b indicate the positions where pressure taps were installed to measure total pressure losses along a lateral line of 21-m length

laterals to carry out experiments at this stage. The internal diameter of polyethylene laterals was determined by measuring 12 samples of each nominal diameter using a digital caliper (resolution 0.01 mm). The nominal diameters of 13, 16, 20 and 26 mm presented the following internal diameters (average value \pm standard deviation): 13.27 ± 0.08 ; 15.92 ± 0.05 ; 20.92 ± 0.07 ; and 26.92 ± 0.09 mm.

Modeling of minor losses caused by start connectors

A combination of theoretical and experimental approaches is often required to develop practical solutions to problems in hydraulics and fluid mechanics (Zitterell et al. 2013). Dimensional analysis can be used to solve problems in fluid flow since it is a simple, clear and intuitive method for determining the functional dependence of physical quantities that influence a process (Vekariya et al. 2010). Dimensional analysis is a useful tool for developing predictive equations, which reduces the physical quantities to dimensionless groups called Pi-terms (Π). The Buckingham Pi theorem enables planning of experimental runs and analysis of measurements by dimensionless groups. Models based on dimensional analysis were developed to estimate pressure losses in drip irrigation laterals (Demir et al. 2007; Perboni et al. 2015), pressure losses in filters (Puig-Bargués et al. 2005; Yurdem et al. 2008; Duran-Ros et al. 2010; Wu et al. 2014), minor losses in microirrigation connectors (Zitterell et al. 2013) and to study hydraulics of microtubes (Vekariya et al. 2010).

In this research, dimensional analysis was based on the Buckingham Pi theorem (Buckingham 1914) and the method of repeating variables, following practical procedures defined by Munson et al. (2002) and Fox et al. (2011).

Dimensional analysis approach to estimate minor losses caused by start connectors inserted along a manifold

The local pressure loss caused by each start connector installed along a manifold is mainly influenced by the protrusion area of the connector into the flow, the fluid properties, the flow velocity through manifold and the manifold diameter. Based on such interpretation of this physical process, the following relationship can be defined:

$$\Delta p_c = f(V_M, D_M, \rho, \mu, A_g) \quad (4)$$

where: Δp_c is the pressure loss caused by a start connector ($\text{ML}^{-1}\text{T}^{-2}$); V_M is the flow velocity at section D_M (LT^{-1}); D_M is the manifold internal diameter (L); ρ is the water density (ML^{-3}); μ is the water dynamic viscosity ($\text{ML}^{-1}\text{T}^{-1}$); and A_g is the protrusion area of a start connector (L^2).

The number of dimensionless groups that can be formed using Buckingham Pi theorem result from the difference between the number of variables that describe a process (k) and the number of reference dimensions (r) required to define units to the list of variables. Equation 4 accounts for six variables ($k = 6$) associated with three reference dimensions (M, L, T) ($r = 3$) so that the number of dimensionless groups is equal to three. Finally, the problem of six variables shown in Eq. 4 can be reduced to a problem of three variables, as shown in Eq. 5.

$$\Pi_1 = \phi(\Pi_2, \Pi_3) \quad (5)$$

Using the method of repeating variables, variables are combined in order to form dimensionless groups, also called Pi-terms (Π). The method requires the selection of the so-called “repeating variables” following a specific set of rules (Munson et al. 2002; Fox et al. 2011). In respect of the problem being modeled, the chosen repeating variables were V_M , D_M and ρ . Thereafter, the repeating variables were systematically combined with the remainder variables in order to define the pi-terms, resulting in Eq. 6.

$$\frac{\Delta p_c}{\rho V_M^2} = \phi\left(\frac{\rho V_M D_M}{\mu}, \frac{A_g}{D_M^2}\right) \quad (6)$$

Equation 6 represents a fundamental relationship that describes the physical process of minor losses caused by start connectors installed along a manifold.

Dimensional analysis approach to estimate minor losses that occur when water flows from a manifold to a lateral through a start connector

Figure 3 illustrates the flow through a start connector used to attach a lateral to a manifold. The local head loss at lateral inlet can be described by at least three components of pressure loss: (a) from the manifold to the connector inlet, there is a sudden contraction followed by expansion of streamlines; (b) from the connector inlet to its outlet, there is a gradual or sudden expansion depending on the connector inner section; and (c) from the connector outlet to the lateral, there is a gradual expansion of streamlines.

Under such circumstances, local head loss is assumed to be influenced by the flow rate through the connector, the fluid properties, and the geometrical characteristics of the manifold, start connector and lateral. Therefore, nine variables ($k = 9$) are expected to influence minor losses caused by start connector installed at laterals inlet (Eq. 7).

$$\Delta p_c = f(V_L, D_L, \rho, \mu, D_{c_{in}}, D_{c_{out}}, L_c, A_r) \quad (7)$$

where: Δp_c is the pressure loss caused by a start connector ($\text{ML}^{-1}\text{T}^{-2}$); V_L is the flow velocity at the lateral inlet (LT^{-1}); D_L is the lateral internal diameter (L); ρ is the water density (ML^{-3}); μ is the water dynamic viscosity

($ML^{-1}T^{-1}$); $D_{c_{in}}$ is the connector's inlet diameter (L); $D_{c_{out}}$ is the connector's outlet diameter (L); L_c is the connector length (L); and A_r is the flow cross section of the manifold where the start connector is located ($A_M = A_r + A_g$) (L^2); A_M is the manifold cross section (L^2).

The physical process involves three reference dimensions (M, L, T) and nine variables so that six dimensionless groups can be formed. The Π were defined by combining the repeating variables V_L, D_L and ρ with the remainder variables, resulting in Eq. 8.

$$\frac{\Delta p_c}{\rho V_L^2} = \Phi \left(\frac{\rho V_L D_L}{\mu}, \frac{D_{c_{in}}}{D_L}, \frac{D_{c_{out}}}{D_L}, \frac{L_c}{D_L}, \frac{A_r}{D_L^2} \right) \quad (8)$$

Fitting and assessment of models

Experimental data collected during the first and second stages of experiments were used to calculate a number of values for each of the pi-terms shown in Eqs. 6 and 8. Thereafter, a multivariate power-law model (Eq. 9) was fitted to the data using the least square method. The number of terms of the power-law model varied according to the model being fitted.

$$\Pi_1 = \beta_1 \Pi_2^{\beta_2} \Pi_3^{\beta_3} \dots \Pi_n^{\beta_n} \quad (9)$$

where β_i represents an empirical coefficient.

The dataset obtained experimentally was randomly divided into two subsets: the calibrating and the testing dataset. The calibrating dataset accounts for 70% of the whole experimental data, and it was used to fit the models. The testing dataset consists of the remaining 30% data, and it was used to assess the accuracy/performance of the models. Models were assessed by the root mean square error (RMSE) and by graphical error analyses. The RMSE is a common index to measure accuracy of models (Duran-Ros et al. 2010; Provenzano et al. 2015) that quantifies differences between estimated and observed values and also enables to compare performance of models. The graphical error analysis, described in the results section, is also useful to estimate prediction errors while evaluating accuracy of models. When a model is assessed by using the testing dataset, such error analysis provides prediction errors associated with their frequency of occurrence.

Results and discussion

Experimental dataset

Minor losses caused by start connectors inserted along a manifold

A dataset accounting for 225 pairs of values of local pressure loss as a function of Reynolds number (Fig. 4) was

obtained from testing five models of start connectors (1–5) and three nominal diameters of PVC manifolds (DN35, DN50 and DN75). The Reynolds number was calculated considering diameters and velocities at the manifold section (D_M, V_M).

As shown in Table 1, protrusion area (A_g) increases from start connectors 1–5. The larger the protrusion area, the higher the local head loss caused by connector's barb. The start connector model 5 presented the highest values of local head loss (Fig. 4), which is a logical result since that connector has the largest protrusion area ($A_g = 345.453 \text{ mm}^2$). Hence, it could be considered the worst choice in terms of local head loss along a manifold. On the other hand, the connector model 1 has the smallest protrusion area ($A_g = 104.105 \text{ mm}^2$) and consequently caused the lowest values of local head loss when compared to the other start connectors. In addition, local head losses decreased as manifold diameter increased, which is also expected to occur because the blockage proportion of the manifold section by the connector's barb decreases as manifold diameter increases. The same hydraulic behavior was reported for online emitters (Al-Amoud 1995; Bagarello et al. 1997; Juana et al. 2002b). Therefore, the curves of local head loss shown in Fig. 4 are consistent with theory.

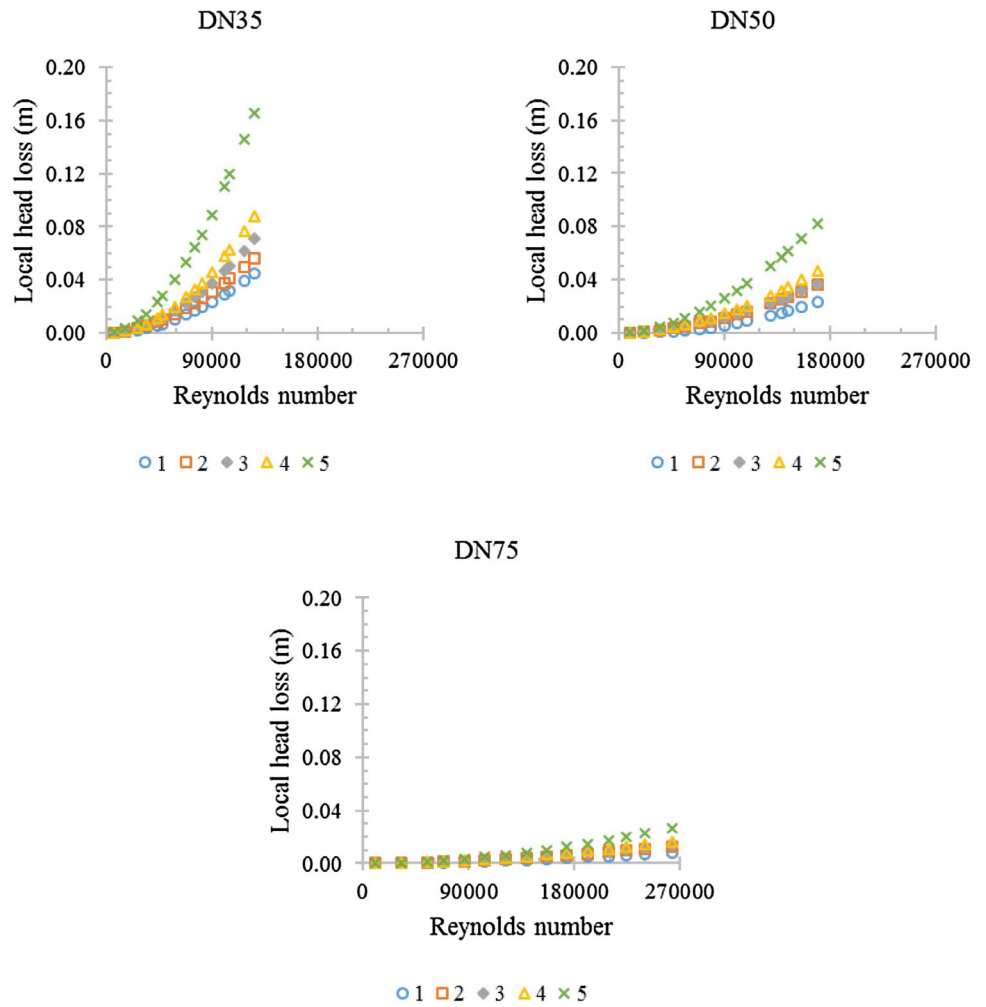
Minor losses that occur when water flows from a manifold into a lateral line through a start connector

A dataset consisting of 881 pairs of values of local pressure loss as a function of Reynolds number (Fig. 5) was obtained from testing combinations of five models of start connectors (1–5), three nominal diameters of PVC manifolds (DN35, DN50 and DN75) and four nominal diameters of polyethylene laterals (DN13, DN16, DN20 and DN26). The Reynolds number was calculated based on the diameters of lateral lines and flow velocities at laterals inlet (D_L, V_L).

In this case, the primary causes of local pressure losses are associated with start connector geometry and flow rate through start connector. These minor losses increase as the connector cross section decrease or, when there are abrupt changes in the inner cross section of connector. Secondary effects are expected to occur due to manifold and lateral cross section and the corresponding degree of contraction or expansion of streamlines. A similar behavior was reported by Zitterell et al. (2013) while studying smaller connectors employed to attach microtubes into polyethylene laterals.

Start connectors model 4 and 5 presented lower values of local head loss than the other models, which makes sense because those connectors have larger flow sections (i.e., $D_{c_{in}}$ and $D_{c_{out}}$) and they do not have abrupt changes in their inner cross section. Therefore, the connectors 4 and

Fig. 4 Experimental data of local head loss caused by start connectors inserted along a manifold. Data obtained from testing five models of start connectors (1–5) and three nominal diameters of PVC manifolds (DN35, DN50 and DN75)



5 are the best choices in terms of local head loss caused at the entrance of laterals. The other three models of connectors presented higher values of local head loss due to the following reasons: connector 1 has the smallest inner cross section among the five models; connectors 2 and 3 have a relatively small inlet section followed by abrupt changes in their inner sections, which induces additional pressure losses when compared to the other models of start connectors.

Modeling minor losses caused by start connectors

Estimating minor losses due to start connectors inserted along a manifold

The empirical coefficients of Eq. 9 combined with Eq. 6 were determined based on the experimental data illustrated in Fig. 4, resulting in Eq. 10.

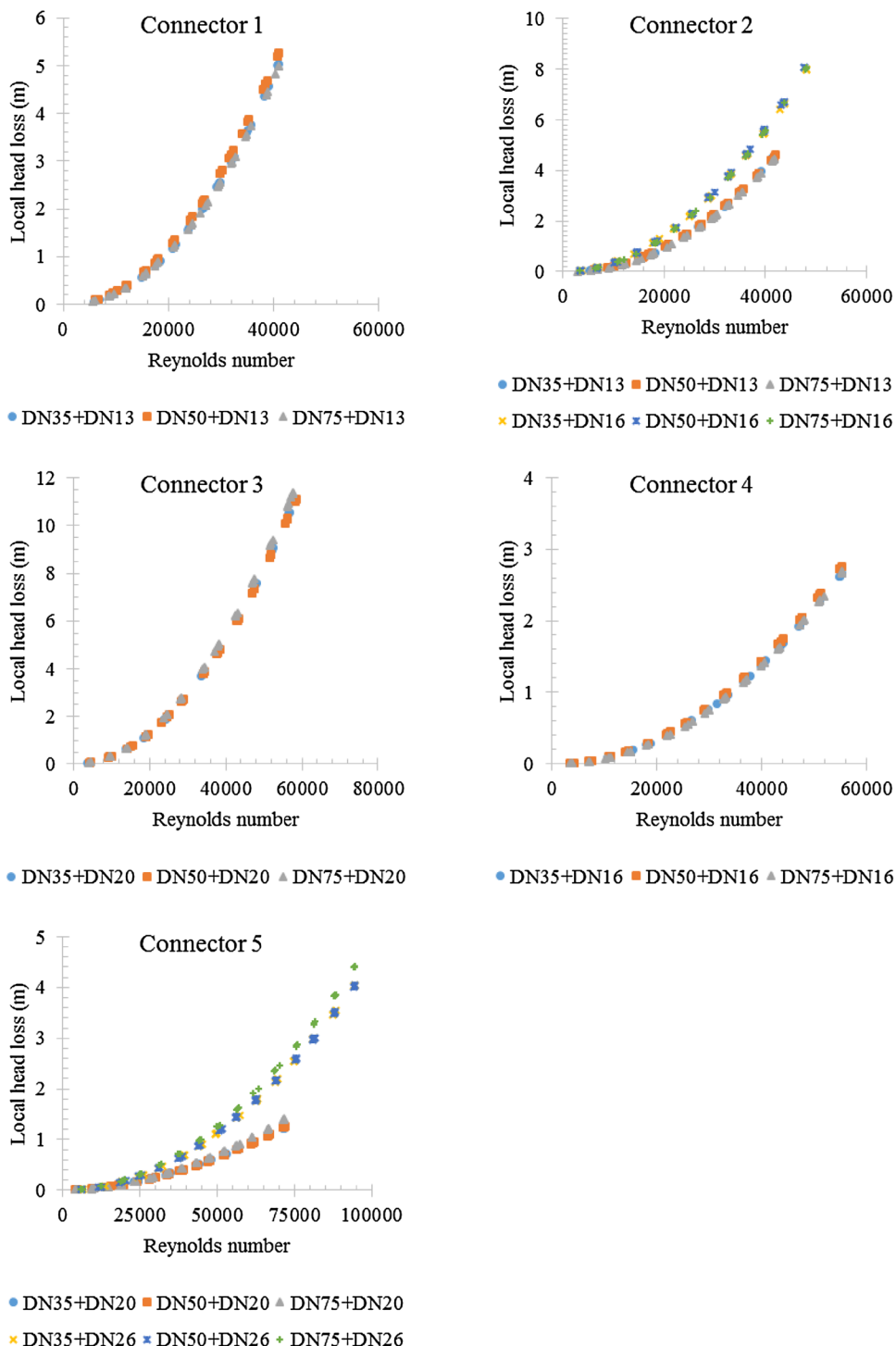
$$\frac{\Delta p_c}{\rho V_M^2} = 2.3311 \left(\frac{\rho V_M D_M}{\mu} \right)^{-0.0937} \left(\frac{A_g}{D_M^2} \right)^{1.1357} \tag{10}$$

Since $\Delta p_c = \rho g h_{fL}$, Eq. 11 corresponds to the model based on dimensional analysis for estimating the local head loss caused by a single start connector inserted into a manifold. Therefore, a step-by-step procedure is required to design manifolds taking into account such minor losses.

$$h_{fL} = 0.2376 \nu^{0.0937} A_g^{1.1357} \frac{V_M^{1.9063}}{D_M^{2.3651}} \tag{11}$$

Equation 11 is valid for: $7056 \leq \frac{\rho V_M D_M}{\mu} \leq 262,888$; $0.0203 \leq \frac{A_g}{D_M^2} \leq 0.2780$. The units of the equation’s terms are: $h_{fL} = \text{m}$; $\nu = \text{m}^2 \text{s}^{-1}$; $A_g = \text{m}^2$; $V_M = \text{ms}^{-1}$; $D_M = \text{m}$.

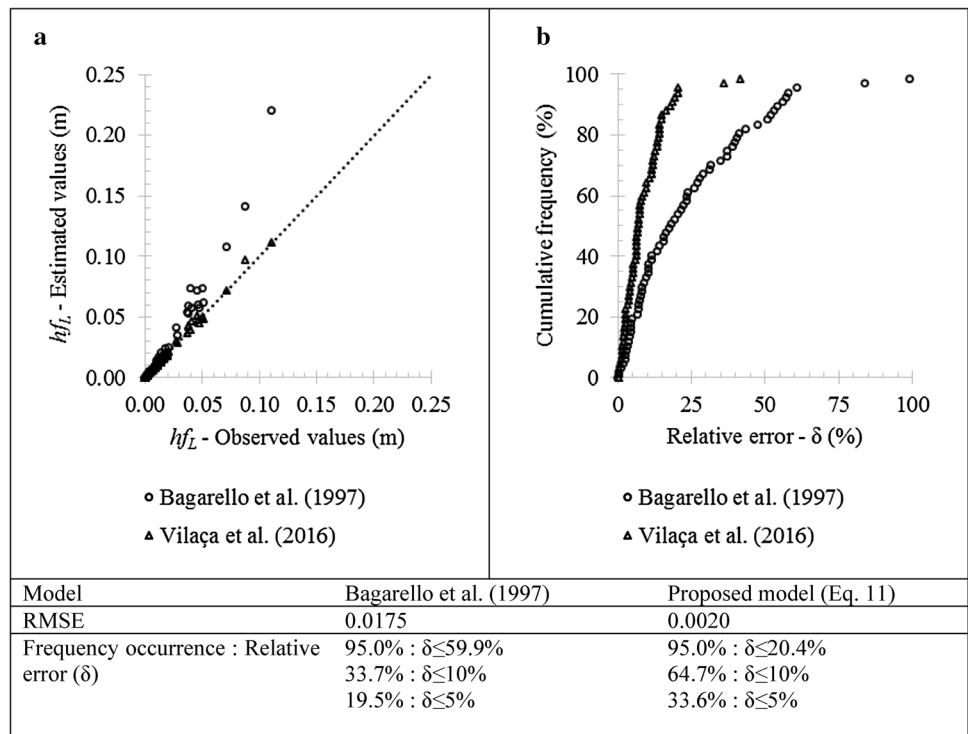
Fig. 5 Experimental data of local head loss that occurs when water flows from a manifold to a lateral line through a start connector. Each chart groups data from a start connector and each data series represents a combination of PVC manifold, start connector and polyethylene lateral



The testing dataset served to validate the proposed model and to compare its predictions against those obtained using the model developed by Bagarello et al. (1997) (Fig. 6). As already mentioned, Bagarello et al. (1997) proposed an equation for estimating minor losses along pipes consisting of online emitters instead of start connectors. In addition, that equation was validated based on experimental results of online emitters attached to polyethylene

(PE) pipes, under Reynolds number ranging from 3971 to 22,171. Although testing conditions reported by Bagarello et al. (1997) were different from those here described, the shape of the protrusion area is practically the same in both researches and the physical phenomenon related to flow is expected to be similar. The comparison of our results against those obtained by Bagarello et al. (1997) aims to link these similar researches and to verify whether the

Fig. 6 Comparison between the proposed model (Eq. 11) and Eq. 1 (Bagarello et al. 1997) on predicting the local head loss due to a single start connector inserted into a manifold: **a** observed versus estimated values of local head loss; **b** graphical error analysis presenting relative errors (δ) versus frequency of errors in predictions of local head loss ($\delta = 100 \left| \frac{\text{observed} - \text{estimated}}{\text{observed}} \right|$)



equation proposed by Bagarello et al. (1997) provides suitable results even beyond the range of conditions in which it was validated.

Based on Eq. 1 and on the combination of PVC pipes (manifold) and start connectors evaluated in this research, the coefficients of local head loss (α) varied from 0.015 to 0.734. A similar range of values was reported by Bagarello et al. (1997), who evaluated six models of online emitters attached to PE pipes of 16 and 20 mm diameter and verified values of α ranging from 0.080 to 1.298.

The interpretation of results shown in Fig. 6 leads to the following observations: (a) Eq. 1 proposed by Bagarello et al. (1997) overestimated values of local head loss (Fig. 6a); (b) the comparison of RMSE values indicates a better accuracy of the proposed model ($0.0020 < 0.0175$); (c) the graphical error analysis (Fig. 6b) demonstrates that the proposed model presents lower relative errors (δ) that also occur less frequently if compared to the model proposed by Bagarello et al. (1997). The importance of Fig. 6b can be clearly understood by the following examples of interpretation: It shows that 95% of predictions using the proposed model presented relative errors of up to 20.4%, while relative errors reached 59.9% considering the model proposed by Bagarello et al. (1997); relative errors of up to 10% were observed in 64.7% of the predictions using the proposed model. Although the shape of the protrusion area is practically the same when one compares online emitters and start connectors, the equation obtained by Bagarello et al. (1997) was less accurate than the proposed one. Such

result is somehow expected since the equation proposed by Bagarello et al. (1997) was not developed neither validated to estimate local head losses due to start connectors. Protrusion areas, pipe diameters and Reynolds numbers values were higher/larger in the current research, and it probably justifies the observed differences in accuracy when comparing both models.

Estimating minor losses that occur when water flows from a manifold into a lateral line through a start connector

Similarly to what was previously described, the empirical coefficients of Eq. 9 combined with Eq. 8 were determined resulting in Eq. 12 (hereafter called the full model) that factors in the whole list of variables needed to estimate local head losses associated with flow through a start connector.

$$\frac{\Delta p_c}{\rho V_L^2} = 0.2569 \left(\frac{\rho V_L D_L}{\mu} \right)^{0.0572} \left(\frac{D_{c_{in}}}{D_L} \right)^{-4.4159} \left(\frac{D_{c_{out}}}{D_L} \right)^{0.0663} \left(\frac{A_r}{D_L^2} \right)^{-0.0235} \left(\frac{L_c}{D_L} \right)^{-0.1218} \quad (12)$$

The selection of variables required to build a model, when several potential predictors are available, represents a frequent problem in regression analysis. Including unnecessary predictors in the model complicates description of the process and may result in poor predictions, while omitting

important effects reduces predictive power (Chatterjee and Simonoff 2013). A model should be as simple as possible while still accounting for the important relationships in the data. An approach to select a subset of variables to build a model consists in defining a criterion that measures how well a model performs, evaluate the criterion for each subset of potential variables and pick the subset that optimizes the criterion (Seber and Lee 2003). Generally the model with the smallest residual mean square should be chosen (Bates and Watts 1988). A variable that does not improve the criterion may be not significant so that it can be deleted.

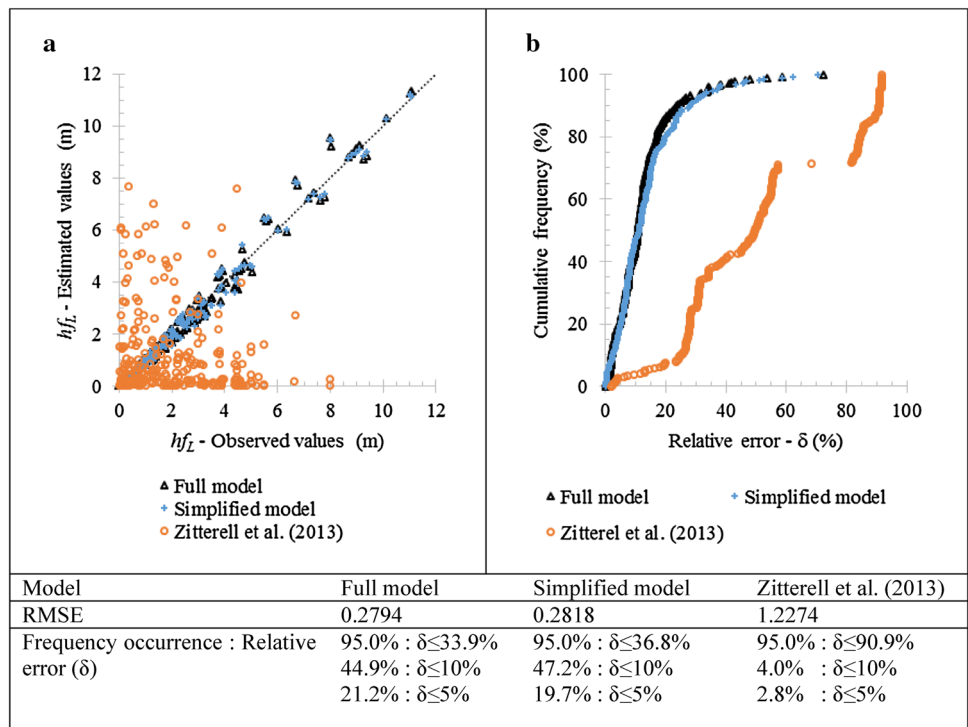
Observed data of local head loss presented very similar values for various manifold diameters (Fig. 5). Such observation indicates that effects of manifold geometry (represented by A_r) can be neglected and removed from the analysis. In addition, the less significant pi-terms of Eq. 12 were identified based on RMSE values and charts of frequency of prediction errors (Fig. 7). Finally, the following simplified model was obtained:

$$\frac{\Delta p_c}{\rho V_L^2} = 0.1860 \left(\frac{\rho V_L D_L}{\mu} \right)^{0.0632} \left(\frac{D_{c_{in}}}{D_L} \right)^{-4.4933} \quad (13)$$

Since $\Delta p_c = \rho g h_{f_L}$ and rearranging terms of Eq. 13, Eq. 14 is obtained and it corresponds to the simplified model for estimating local head losses at lateral inlet due to a start connector.

$$h_{f_L} = \frac{0.0190 V_L^{2.0632} D_L^{4.5565}}{\nu^{0.0632} D_{c_{in}}^{4.4933}} \quad (14)$$

Fig. 7 Comparison of the full model, simplified model and Eq. 3 (Zitterell et al. 2013) on predicting minor losses that occur when water flows from a manifold to a lateral line through a start connector: **a** observed versus estimated values of local head loss; **b** graphical error analysis presenting relative errors (δ) versus frequency prediction errors



Equations 12 and 14 are valid for: $3026 \leq \frac{\rho V_L D_L}{\mu} \leq 94536$; $0.4147 \leq \frac{D_{c_{in}}}{D_L} \leq 0.7672$; $0.5721 \leq \frac{D_{c_{out}}}{D_L} \leq 0.8538$; $0.8933 \leq \frac{A_r}{D_L^2} \leq 22.5599$; $1.9435 \leq \frac{L_c}{D_L} \leq 4.3765$.

The units of the equation's terms are: $h_{f_L} = m$; $\nu = m^2 s^{-1}$; $V_L = m s^{-1}$; $D_L = m$; $D_{c_{in}} = m$.

The data scattering in Fig. 7a, the high relative errors shown in Fig. 7b and the RMSE value of 1.2274 clearly indicate that the model proposed by Zitterell et al. (2013) did not fit the testing dataset. For example, relative errors lower than 10% were observed in just 4% of the predictions, while 95% of predictions presented relative errors of up to 90.9%. Such result is justified by the fact that the empirical coefficients of that model were fitted based on experimental data that does cover the conditions described in this research.

Figure 7 also enables a comparison to be made between the full model (Eq. 12) and the simplified model (Eq. 14). The RMSE values were very similar (i.e., 0.2794 and 0.2818), and the frequency of occurrence associated with values of relative errors (Fig. 7b) also indicates similar accuracy of both models. Although the full model presented a slightly better accuracy, in practice, the simplified model is preferred since it requires less parameters and is simpler to use.

The local head loss associated with flow through a start connector is confirmed to be mainly influenced by the flow rate through the connector, the fluid properties and the inlet

diameter of the connector. The diameters of the manifold and lateral line, as well as the other geometrical characteristics of start connectors, exert secondary influence on minor losses since the model accuracy practically has not changed when such variables were removed from the full model (Eq. 12).

Relevance of minor losses due to start connectors in hydraulics of microirrigation subunits

Hydraulic simulations were undertaken to assess the relevance of minor losses due to start connectors in the hydraulics of subunits. Simulations were based on a backward step-by-step procedure. Friction losses (h_f) were estimated using the Darcy–Weisbach formula with friction factor calculated by Eq. 15 (Swamee 1993), which is valid for the full range of flow regimes. Total head loss resulted from the sum of friction head losses and local head losses.

$$f = \left\{ \left(\frac{64}{Re} \right)^8 + 9.5 \left[\ln \left(\frac{\epsilon}{3.7D} + \frac{5.74}{Re^{0.9}} \right) - \left(\frac{2500}{Re} \right)^6 \right]^{-16} \right\}^{0.125} \tag{15}$$

Lateral design

Simulations were performed to quantify the importance of minor losses associated with start connectors while designing lateral lines. Minor losses due to protrusion of emitters along the lateral ($h_{f_{lc}}$) were determined based on Eq. 1, assuming a coefficient of local head loss (α) equal to 0.3. The local head loss at lateral inlet due to a start connector ($h_{f_{lc}}$) was calculated based on the simplified model proposed in this research (Eq. 14).

The following input data were used:

- Lateral line: zero slope; pipe surface roughness (ϵ) = 4 μm ; internal diameter: 13.9 mm for start connectors 1, 2 and 4, and 17.7 mm for start connectors 3 and 5;

- Pressure-compensating emitters: nominal flow rate = 2.3 L h⁻¹; range of working pressure head = 10 to 25 m;
- Water kinematic viscosity of 1.01 $\times 10^{-6}$ m² s⁻¹;
- Lateral lengths were designed assuming maximum and minimum pressure heads of 25 and 10 m, respectively.

Table 2 summarizes simulations performed to quantify the percentage of minor losses induced by start connectors installed at lateral inlet. The lateral length (L_{max}) corresponds to the maximum length calculated for each lateral diameter (D_L) taking into account friction losses (h_f) and minor losses caused by the emitters’ protrusion along the lateral ($h_{f_{lc}}$). Once the lateral was designed, the local head loss due to flow through a start connector ($h_{f_{lc}}$) and the total head loss (h_F) along the lateral were calculated. Results demonstrate that geometry of start connectors has significant influence on $h_{f_{lc}}$. Minor losses of start connectors 1, 2 and 4 were evaluated considering a lateral of 13.9-mm diameter. Start connector 4 presented the lowest local head loss ($h_{f_{lc}} = 0.448$ m), representing 16.1% of minor losses and 2.92% of total head loss along the lateral. It is reasonable since that connector has the largest inlet diameter ($D_{c_{in}} = 9.833$ mm) and it does not have abrupt changes in inner section. On the other hand, the local head losses due to start connectors 1 and 2 reached about 33% of minor losses and 7% of total head loss. Start connector 1 has the smallest inner section among the models evaluated. Start connector 2 also has a small inlet diameter combined with a gradual expansion in its inner section that increases pressure losses. Although minor losses due to start connectors represented a relative small percentage of total head loss (from 0.48 to 7.31%), such amount of pressure loss may be significant while undertaking rigorous hydraulic simulations that require accurate estimation of pressure losses.

Table 3 enables the quantification of the relevance of minor losses due to start connectors in the design of lateral lines. The maximum lateral lengths were calculated taking into account minor losses due to start connectors and neglecting it. Simulations indicate that the maximum

Table 2 Percentage of minor losses associated with start connectors installed at lateral inlet

D_L (mm)	L_{max} (m)	Q (L/h)	h_f (m)	$h_{f_{lc}}$ (m)	Start connector	$h_{f_{lc}}$ (m)	$h_{f_{lc}}/h_{f_L}$ (%)	h_F (m)	$h_{f_{lc}}/h_F$ (%)
13.9	222.0	680.8	12.565	2.331	1	1.175	33.5	16.071	7.31
					2	1.113	32.3	16.009	6.95
					4	0.448	16.1	15.344	2.92
17.7	331.5	1016.6	11.982	2.957	3	1.150	18.0	15.590	4.18
					5	0.072	2.4	15.011	0.48

Q flow rate at lateral inlet, h_f friction head loss, $h_{f_{lc}}$ minor losses caused by protrusion of emitters along the lateral, h_{f_L} local head loss due to start connector at lateral inlet, $h_{f_L} = h_{f_{lc}} + h_{f_{lc}}$ minor losses along the lateral, h_F total head loss

lateral length decreases due to minor losses caused by start connectors that varied from 0.5 to 3.0%. Therefore, minor losses that occur when water flows from a manifold to a lateral line through a start connector can be neglected for design purposes. It supports simplified designing approaches such as those proposed by Baiamonte et al. (2015) and Baiamonte (2016), in which local head losses were neglected and even though the obtained results would be suitable for most of practical applications. In these studies, approaches to obtain optimal designs of paired drip laterals laid on uniformly sloped fields were proposed under the hypotheses that local head losses could be neglected.

Manifold design

Simulations were performed to quantify the importance of minor losses associated with start connectors while designing manifolds. Minor losses due to protrusion of start connectors along the manifold (h_{fL}) were determined based on Eq. 11. The following input data were used:

- Manifold: zero slope; pipe surface roughness (ϵ) = 10 μm ;
- Average flow rate of lateral lines assumed to be constant = 680.8 L h^{-1} ; laterals spacing = 3.8 m;
- The manifold lengths (L) shown in Table 4 correspond to the maximum length calculated for each manifold diameter (D_M) taking into account only friction losses (h_f) and assuming an allowable pressure head variation of 10 m.

Table 4 enables the quantification of the relevance of minor losses due to start connectors in the design of manifolds. The smaller the manifold diameter, the more significant becomes the minor losses due to start connectors. Overall, minor losses represented from 1.9 to 14.6% of total energy losses along manifolds (nominal diameter 35, 50 and 75). Minor losses caused by protrusion of emitters barbs into polyethylene pipes of 13 and 25 mm represent

an increase from 5 to 32% in the energy losses (Al-Amoud 1995). Local head losses represented from 6.4 to 49.5% of total energy losses in simulations for designing drip lateral lines considering two models of pipes with integrated coextruded emitters (Provenzano and Pumo 2004).

Although each start connector contributes a small amount of pressure loss, the sum of all these minor losses along a manifold become significant when compared to the overall energy loss. Similar conclusion was reported to emitters installed along laterals (Yildirim 2007).

Conclusions

Minor losses due to start connectors were separated into two components: (a) minor losses due to the protrusion of start connectors inserted along a manifold and (b) minor losses that occur when water flows from a manifold into a lateral line through a start connector. Equations based on dimensional analysis were developed and validated to estimate both components of minor losses. Predictions obtained by the proposed models were more accurate than those obtained by similar models available in the literature.

Two models based on dimensional analysis were developed to estimate minor losses that occur when water flows from a manifold into a lateral line through a start connector. Although the so-called full model presented a slightly better accuracy, in practice, the simplified model is preferred since it requires less parameters and is simpler to use. The local head loss associated with flow through a start connector is confirmed to be mainly influenced by the flow rate through the connector, the fluid properties and the inlet diameter of the connector. The diameters of the manifold and lateral line, as well as the other geometrical characteristics of start connectors, exert secondary influence on minor losses since the model accuracy practically has not changed when such variables were removed from the full model.

The obtained model for estimating the local head loss caused by a single start connector inserted into a manifold

Table 3 Effect of minor losses due to start connector in maximum lateral length

PE pipe (DN)	D_L (mm)	Start connector	L_{\max} (m)	$L_{\max 2}$ (m)	Results for $L_{\max 2}$				ΔL_{\max} (%)
					Q (L/h)	h_f (m)	h_{fL} (m)	h_{fL} (m)	
16	13.9	1	222.0	215.25	660.1	11.651	2.147	1.117	3.0
		2		216.00	662.4	11.763	2.169	1.058	2.7
		4		219.75	673.9	12.332	2.284	0.253	1.0
20	17.7	3	331.5	321.75	986.7	11.106	2.722	1.084	2.9
		5		330.00	1012.0	11.907	2.937	0.072	0.5

Q flow rate at lateral inlet, L_{\max} maximum lateral length neglecting minor losses due to start connectors, $L_{\max 2}$ maximum lateral length taking into account minor losses due to start connectors, $\Delta L_{\max} = 100 \left(1 - \frac{L_{\max 2}}{L_{\max}} \right)$ decrease in maximum lateral length due to start connectors at lateral inlet

Table 4 Percentage of minor losses associated with start connectors installed along manifolds

Manifold (DN)	D_M (mm)	L (m)	Q_M (m ³ h ⁻¹)	h_f (m)	Start connector	h_{fL} (m)	h_F (m)	h_{fL}/h_F (%)
35	35.72	72.2	12.935	9.395	–	–	9.395	–
					1	0.414	9.809	4.2
					2	0.627	10.022	6.3
					3	0.664	10.058	6.6
					4	0.921	10.316	8.9
					5	1.609	11.004	14.6
50	47.56	121.6	21.786	9.849	–	–	9.849	–
					1	0.285	10.134	2.8
					2	0.472	10.322	4.6
					3	0.500	10.349	4.8
					4	0.694	10.543	6.6
					5	1.212	11.061	11.0
75	72.05	250.8	44.933	9.845	–	–	9.845	–
					1	0.192	10.037	1.9
					2	0.291	10.136	2.9
					3	0.308	10.153	3.0
					4	0.427	10.272	4.2
					5	0.746	10.591	7.0

h_f friction head loss, h_{fL} minor losses caused by protrusion of start connectors along manifold, h_F total head loss

was validated within the following ranges: $7056 \leq \frac{\rho V_M D_M}{\mu} \leq 262,888$; $0.0203 \leq \frac{A_g}{D_M^2} \leq 0.2780$. Like-

wise, both models for estimating minor losses that occur when water flows from a manifold into a lateral line through a start connector were validated within the following ranges: $3026 \leq \frac{\rho V_L D_L}{\mu} \leq 94,536$; $0.4147 \leq \frac{D_{cin}}{D_L} \leq 0.7672$; $0.5721 \leq \frac{D_{cout}}{D_L} \leq 0.8538$; $0.8933 \leq \frac{A_r}{D_L^2} \leq 22.5599$; $1.9435 \leq \frac{L_c}{D_L} \leq 4.3765$.

Simulations were undertaken to assess the relevance of minor losses due to start connectors in hydraulics of subunits. Local head losses at laterals inlet due to start connectors represented from 0.48 to 7.31% of total energy losses and from 2.4 to 33.5% of minor losses. Simulations also indicated a decrease in the maximum lateral length due to minor losses caused by start connectors, which varied from 0.5 to 3.0%. Therefore, minor losses that occur when water flows from a manifold to a lateral line through a start connector can be neglected for designing purposes. On the other hand, minor losses due to start connectors installed along manifolds represented from 1.9 to 14.6% of total energy losses (nominal diameters of 35, 50 and 75). Although minor losses due to start connectors represented a relative small percentage of total head losses, such effects may be significant while undertaking rigorous hydraulic

simulations that require accurate estimation of pressure losses.

Acknowledgements The authors are grateful to the following Brazilian institutions for their financial support: the Federal Department of Science and Technology (MCT); the National Scientific and Technological Development Council (CNPq); the Sao Paulo State Scientific Foundation (FAPESP) and the National Institute of Science and Technology in Irrigation Engineering (INCTEI).

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