Provenzano, G.; Alagna, V.; Autovino, D.; Manzano Juarez, J.; Rallo, G. (2016). Analysis of Geometrical Relationships and Friction Losses in Small-Diameter Lay-Flat Polyethylene Pipes. Journal of Irrigation and Drainage Engineering. 142(2):1-9. doi:10.1061/(ASCE)IR.1943-4774.0000958.

Analysis of geometrical relationships and friction losses in small diameter lay-flat polyethylene pipes

Giuseppe Provenzano[1], PhD, Vincenzo Alagna[2], Dario Autovino[3], Juan Manzano[4], PhD, and Giovanni Rallo[5], PhD

[1]Associate Professor, Dipartimento Scienze Agrarie e Forestali, Università di Palermo, Viale delle Scienze 12, Ed. 4, 90128 Palermo, Italy (corresponding author). E-mail: giuseppe.provenzano@unipa.it

[2]PhD Student, Dipartimento Scienze Agrarie e Forestali, Università di Palermo, Viale delle Scienze 12, Ed. 4, 90128 Palermo, Italy. E-mail: vincenzo.alagna@unipa.it

[3]PhD Student, Dipartimento Scienze Agrarie e Forestali, Università di Palermo, Viale delle Scienze 12, Ed. 4, 90128 Palermo, Italy. E-mail: dario.autovino@unipa.it

[4]Professor, Departamento de Ingeniería Rural y Agroalimentaria, Universitat Politécnica de Valencia, Camino de vera s/n, 46022 Valencia, Spain. E-mail: juamanju@agf.upv.es

[5]Felloship Researcher, Dipartimento Scienze Agrarie e Forestali, Università di Palermo, Viale delle Scienze 12, Ed. 4, 90128 Palermo, Italy. E-mail: giovanni.rallo@unipa.it

Abstract

The use of lay-flat polyethylene pipes for microirrigation of horticultural crops has been receiving a widespread attention in the last few decades. The industry has made significant improvements in the hydraulic performance of lay-flat pipes, so that their use is still expected to increase, mainly because of the enhanced competition for water worldwide, that imposes the use of irrigation systems with potentially high application efficiencies and characterized by a limited installation costs.

However, even if hydraulic design procedures for conventional microirrigation systems are fairly

well established, there is still the need to know how different pipe wall thicknesses of lay-flat pipes can affect the pipe geometry under different operating pressures and the related consequences on friction losses.

This paper, after comparing two different procedures, i.e. caliper and photographic method, to assess the geometry of lay-flat polyethylene pipes under different operating pressures, usual in practical applications, analyzes the friction losses per unit pipe length, in order to identifies and to assess a procedure for their evaluation.

Hydrostatic tests, initially carried out on pipes with wall thicknesses of 0.15, 0.20 and 0.25 mm (6, 8 and 10 mil), evidenced that the pipe vertical and horizontal dimensions measured with both the methods are quite similar, even if the maximum standard deviations associated to the caliper, equal for the three pipes to 0.11 mm, 0.19 mm and 0.10 mm, resulted higher than those obtained with the photographic method, whose values resulted generally lower than 0.06 mm. At the same time, the tests allowed to identify that most of the changes of the pipe dimensions occur in the range of pressure from 0 kPa to about 30 kPa, being the dimensions quite similar at higher values, when the pipes tend to assume a round cross section. When water pressures increase over a certain limit, p_{lim}, both vertical width and horizontal height still tend to rise, because of the pipe deformation due to the elasticity of the material, with a trend that resulted more marked for the pipe with the lowest thicknesses. According to the experimental data, the relationships between the pipe effective diameter, to be used to evaluate pipe friction loss, and the water pressure, were then determined on the three considered pipes.

On the other side, based on measured friction losses and on pipe effective diameters, it was verified that the relationship between the Darcy-Weisbach friction factor, f, and the Reynolds number, R, can be still described with a power equation in which, by assuming a value of -0.25 for the exponent, the coefficient resulted lower than the theoretical and equal to c=0.285.

For the three investigated pipes the errors associated to estimated friction loss per unit pipe length were finally evaluated by considering: i) the experimental relationships between friction factor and

Reynolds number and between pipe diameter and operating pressure (case A); ii) the same value of c, but pipe effective diameters of 16.20 mm, 16.10 mm and 15.85 mm corresponding p=p_{lim} (case B); iii) the standard procedure, with a value of c=0.302 and the pipe diameter equal to 16.10 mm, as suggested by the manufacturer. According to the RMSE values associated to friction factor per unit pipe length, lower for the case A, it was observed that a suitable estimation of friction loss per unit pipe length needs to consider the variations of the pipe effective diameter with water pressure, once disposing of a suitable criterion to estimate the friction factor. On the other hand, incorrect values of pipe diameter combined with a inexact values of the friction factor, generate inaccurate estimations of friction loss, with unavoidable consequences in the pipe design.

Key-words: Lay-flat polyethylene pipes, Pipe geometry, Hydraulic radius, Friction losses, Friction factor

Introduction

Despite lay-flat tubing of different plastic materials have been introduced in the sixties for irrigation networks, small diameters thin-walled drip-laterals have been recently diffusing, mainly to irrigate seasonal horticultural crops and with the aim to reduce the installation costs. These drip-lines, with diameters ranging between 12 mm and 22 mm and co-extruded emitters at different spacing, are usually manufactured by thin-walled low density polyethylene pipes, so that they are used under working pressure, *p*, generally lower than 150 kPa. Wall thickness varies between 6 mil and 25 mil, corresponding to 0.15 mm and 0.63 mm, respectively. Compared to the thick-walled pipes, characterized by wall thicknesses ranging between 0.90 mm and 1.20 mm, which are less flexible, thin walled pipes become flat when empty, so they can be wrapped in rolls, easier to be transported (Provenzano et al., 2014).

The shape of such pipes and their degree of roundness depend on the pressure of water inside the pipe: when the working pressure approaches to the lowest limit suggested by the manufacturer, the pipe cross section tends to become flat, whereas it is round when water pressures exceed a certain limit.

Usually, lay-flat drip irrigation systems are designed by considering conventional methods, assuming that the pipe cross sections is circular and the internal diameters as provided by the manufacturers. Only a few years ago, Thompson et al. (2011) emphasized the lack of information necessary to the accurate design of lay flat drip irrigation systems. These Authors, based on an experimental analysis carried out by using pipes with wall thickness of 0.125, 0.20, 0.25 and 0.50 mm, evidenced that estimation of friction losses can be improved if the pipe section is still considered circular, but assuming an effective diameter, lower than the actual, dependent on the pressure inside the pipe.

At increasing operating pressure in fact, the cross-sectional area becomes bigger and, starting from a quasi-rectangular, it tends to assume a round shape, as showed in fig. 1. These changes result in a variation of the cross sectional area and can affect the velocity distribution of pipe flow, with the consequence that the velocity distribution along the vertical direction could be different than the horizontal one. Most of the energy loss is dissipated in the thin layer close to the pipe (boundary layer), where friction plays an important role; on the other hand, in the region outside this layer, friction can be neglected (Provenzano et al., 2007). At decreasing water pressure, when the area and the degree of roundness decrease, the boundary area tends to become larger in proportion of the cross sectional area (Humpherys and Lauritzen, 1964).

Being the friction coefficient dependent on the relative roughness and the velocity distribution, any change in the shape of the cross section affects both these variables and consequently the friction losses. At the same time, pressure along the pipe is influenced by both friction losses and elevation changes. When a lay-flat pipe is laid horizontally, its geometry varies from one section to another along the flow direction, according to the reduction of pressure head. The flow regime assumes therefore a steady state condition and friction loss along a certain pipe length is quite difficult to determine (Rettore Neto et al., 2014).

When the flow velocity distribution is known, its average value can be determined by integrating the velocity profile, so that the flow resistance law can be deduced, as theoretically done by circular and very wide rectangular shapes, under specific boundary conditions (von Karman, 1934; Prandtl, 1935). According to the Darcy-Weisbach equation, for a circular pipe having an internal diameter equal to d, friction loss h_f along a pipe length L, can be expressed as:

$$h_f = \frac{f}{d}\frac{V^2}{2g}L = \frac{8f}{g\pi^2}\frac{Q^2}{d^5}L \qquad (1)$$

in which f is the friction factor, V the mean flow velocity, Q the flow rate and g the acceleration of gravity.

The friction coefficient in smooth pipes is usually evaluated as a function of Reynolds number, R, by the Blasius equation, valid for quasi-turbulent flow in smooth pipes or similar equations, specifically obtained for small diameter polyethylene pipe (von Bernuth and Wilson, 1989; Hathoot et al., 1993; Bagarello et al. 1995; Juana et al., 2002; Provenzano and Pumo, 2004):

$$f = \frac{c}{R^{0.25}} \qquad (2)$$

in which c is a constant that, for small diameter polyethylene pipe, can be assumed equal to 0.302 (Bagarello et al. 1997; Provenzano et al., 2005).

For low pressure lay-flat drip lines, whose cross section can be non-circular, the internal diameter d appearing in eqs. (1) and (2), has to be replaced by a value equal to four times the hydraulic radius, R_h, of the new shape (Streeter and Wylie, 1985):

$$d = 4R_h = 4\frac{A}{P} \qquad (3)$$

in which A is pipe cross sectional area and P is the perimeter of the pipe cross sections. Eq. (3) provides reasonably precise results for turbulent flow, but it is not very accurate when the flow regime is laminar (Finnemore and Franzini, 2002). Assuming that for low values of operating pressure the pipe cross section can be hypothesized as constituted by a circle segment having a certain radius, r, mirrored respect to its chord, and subtending an angle ω (radians) with the circle center, the total area, A, and the wetted perimeter, P, result:

$$A = r^2(\omega - sen\varpi) \qquad (4)$$

$$P = 2\omega r \qquad (5)$$

Only recently, Rettore Neto et al. (2014) developed a procedure to determine friction loss along elastic pipe, based on eq. (1) and accounting for the variability of pipe cross section with the internal water pressure. The new equation, named as “pressure dependent head loss equation” (PDHLE), needs the knowledge of the modulus of elasticity of pipe material, as well as pipe wall thickness, working pressure and the variations of internal diameter due to pressure. Anyway, the proposed methodology takes only into account the elastic deformation of the pipe due to external forces in a range of internal pressures unusual for practical applications and does not consider the changes in the shape of pipe cross-section occurring at the lowest operating pressures.

A question that still needs to be solved is how different wall thicknesses of lay-flat polyethylene pipes affect the tube geometry under different operating pressures and the related effects on friction losses.

A specific experimental investigation was therefore carried out in order i) to compare two different procedures, i.e. caliper and photographic method, to measure the pipe horizontal width and vertical height under different operating pressures; ii) to model the pipe effective diameter as a function of water pressure and iii) to analyze the values of friction losses per unit pipe length in deformable polyethylene pipes characterized by different wall thickness, with the aim to identify and to assess a general procedure for their evaluation.

Materials and methods

Hydrostatic tests

In order to determine the relationships between the pipe dimensions, i.e. horizontal width and vertical height, and pressure head, hydrostatic tests were carried out on thin-walled polyethylene pipes, having nominal diameter, *ND*, equal to 16 mm and characterized by three different pipe wall thicknesses (6 mil, 8 mil, 10 mil). According to the manufacturer, all the pipes have the same internal diameter, *d*, (d=16.10 mm) and should be used under operating pressures ranging between 30 kPa and 100-120 kPa.

For each examined pipe, two 1.0 m long sections were connected to two vertical bars, as showed in fig. 2, and positioned to measure, for different hydrostatic pressures, horizontal width (D_h) and vertical height (D_v). Fittings and valves were coupled in such a manner that water could entry in the tubes and drain from it. At the same time, the corresponding water pressures were measured by using a mercury gauge equipped with an air vent and connected to the pipes. To reduce the water pressure in the network, a diaphragm pressure regulating valve was inserted along the inflow pipe.

With the aim to eliminate the effect of round end fittings, the horizontal and vertical dimensions were measured three times in the middle section of the pipes (fig. 2), by means of a digital caliper having a precision of 0.01 mm (caliper method). At the same time two pictures were taken and used to measure the corresponding pipe dimensions with a CAD software (photographic method). About thirty measurements for each pipe wall thickness were carried out at least half an hour after establishing each value of hydrostatic pressure, in order to avoid further pipe deformations. To increase the accuracy of the measurements, the order of pressure was established randomly and each determination was repeated twice. Pressure values ranged between about 10 kPa and 150 kPa, wider than the interval of working pressures suggested by the manufacturer.

Hydrodynamic tests

Hydrodynamic tests were carried out by using the same three thin-walled polyethylene pipes used for the hydrostatic ones (*ND* 16), in order to measure friction losses under different pressure heads and flow rates. The experimental setup, shown in Fig. 3, was fed by a recirculation pump (Ep). A water tank (T), installed about 20 m below the pipe and a diaphragm pressure regulating valve, allowed to establish a constant value of pressure head in the hydraulic circuit, in which there were inserted three trams of pipe, having the same length (L=11.8 m). Two air vents were placed in correspondence to the differential manometer to facilitate the removal of air bubbles at the begin of each experiment.

Twelve measurements were acquired on each pipe, by considering a wide range of flow rates and pressure heads, so to obtain an extensive range of Reynolds numbers, usual in practical applications. The pipe length was also measured to take into account possible longitudinal dilatations.

A differential manometer was used to measure head losses in the three trams in which each pipe was divided (P_1-P_2, P_3-P_4, P_5-P_6), while a pressure gauge provided the pressure head, h_{P1}, at the pipe upstream end (P1). Operating in this way it was possible to dispose, for each pipe thickness, of 36 runs characterized by different geometric and hydraulic conditions. For each operating pressure, head losses, including local losses at fitting connections installed at the upstream and downstream end of each tram, were measured three times, after reaching a steady state condition. Accuracy of the pressure gauge readings was equal to 0.05 mmHg, so that the error on measured head loss resulted about 1.0 mm.

During each experiment, the flow discharge, constant through the three trams of pipe, was measured three time at the downstream end of the circuit, by acquiring the time necessary to fill a volume of about 10 l; water was weighted with a precision of 0.1 g, and the actual water density was determined based on the detected temperatures. In order to avoid systematic error, discharges in experimental tests were assigned randomly (von Bernuth and Wilson, 1989).

Table 1 shows minimum and maximum values of pressure head at the upstream end, of flow rate and of Reynolds number, as measured during the experiments. The latter values were obtained considering the pipe with a circular cross section, equivalent to the actual measured.

With the aim to evaluate the local losses caused by the fitting connectors at the manometric gauges, a specific experiment was carried out by using the same experimental setup, that was adapted for the purpose. A short tram of pipe with wall thickness of 8 mil and a length of 0.30 m, was connected to the manometric gauges (P_1-P_2), with the same connectors already used to determine friction losses. Total pressure losses (friction and local losses) were then measured under pressures variable from 0.6 kPa to 168.3 kPa and by considering fifteen different flow rates, ranging between 236.1 l/h and 1491.4 l/h. Each determination was repeated three times, in order to reduce experimental errors. Water temperature was also measured during each experiments, whereas horizontal and vertical dimensions in the middle cross section of the pipe, were determined once known the specific relationship between the effective pipe internal diameter, d, and water pressure, p. For each flow rate, local losses due to the fittings were then determined by subtracting to the measured total losses, the corresponding friction losses in the pipe, estimated by assuming the pipe circular and based on eqs. (1) and (2).

Results and discussion

Hydrostatic tests

For the considered pipes, fig. 4a-c shows the external vertical heigth, D_v, and horizontal width, D_h, measured with the photographic method on pipe with wall thicknesses of 6, 8 and 10 mil, as a function of the corresponding values obtained by the caliper. Horizontal and vertical bars indicate the standard deviations, σ, of the measurements carried out by means of the two methodologies, whose values are illustrated in detail in Fig. 5a-c. As can be observed, the values of external pipe dimensions measured by the photographic method resulted quite similar to the corresponding obtained with the caliper (fig. 4a-c), even if the latter are generally characterized by higher standard deviations (fig. 5a-c) than the former. In particular, with the caliper method, the maximum standard deviation resulted equal to 0.11 mm, 0.19 mm and 0.10 mm for wall thickness of 6 mil, 8 mil and 10 mil respectively, whereas they resulted, at maximum, slightly higher than 0.06 mm when considering the photographic method.

Because of the lower variability characterizing the pipe dimensions measured by the photographic method compared to the caliper, the following analysis were carried out by considering the former methodology.

Based on the measured values of external pipe dimensions, the corresponding internal width, d_h, and height, d_v, were then calculated by subtracting twice the pipe wall thickness, equal to 0.15 mm, 0.20 mm and 0.25 mm respectively, for the three considered pipes.

Fig. 6a-c illustrates, as a function of water pressure, the variations of internal vertical height and horizontal width, obtained with the photographic method on pipe with wall thicknesses of 6, 8 and 10 mil. As can be observed, for all the examined cases, the vertical heights rapidly increase, whereas the horizontal widths decrease, when hydrostatic pressure rises from 0 kPa to about 30 kPa; on the other hands, both the dimensions tend to became similar for the highest values of hydrostatic pressure and the pipes tend to assume a round cross section (d_v=d_h). Moreover, for the pipes with wall thickness of 6 mil and 8 mil, both d_v and d_h tend again to rise when water pressure results higher than a certain threshold values, as a consequence of the pipe deformation due to the elasticity of the material; as visible, this trend is more marked for the pipe characterized by the lowest thickness.

Fig. 7 shows the degree of pipe roundness obtained, for the examined pipes, by dividing the vertical height by the horizontal width. As observed by Humphreys and Lauritzen (1962) for polyvinylchloride plastic and butyl-rubber tubes with diameters ranging between 100 mm and 400 mm, even for low diameter polyethylene pipes, depending on the pressure inside the pipe, the degree of pipe roundness increases and consequently the pipe cross-sectional area tends rapidly to inflate, till to reach a round cross section.

Based on the measurements of widths and heights in the range of pressures for which pipe is not circular and assuming the shape of the cross section as constituted by two circle segments, the cross sectional area and the wetted perimeter were therefore determined by using eqs. (4) and (5). Each circle segment is characterized by a radius, r, still variable with the water pressure, that was evaluated from eq. (5), as a function of the subtended angle ω and superimposing that, in the range of examined pressures, the wetted perimeter P remains constant.

The value of ω was obtained by solving, with an iterative procedure, the equation:

$$\omega = 2\arctan\left(\frac{d_h}{2r - d_v}\right) \qquad (6)$$

whereas the values of the wetted perimeter P was assumed the one corresponding to the minimum pressure threshold, to which the pipe become circular.

For each water pressure therefore, once identified the shape and determined the cross sectional area and the wetted perimeter, it was possible to evaluate the hydraulic radius and then, by eq. (3), the corresponding value of pipe effective diameter to be used in eqs. (1) and (2).

Fig. 8 shows the values of the effective diameter, *d*, as a function of water pressure, *p*. As can be observed, the values of effective diameters resulted slightly increasing in the ranges of operating pressure from about 3 to 80 kPa (6 mil), 5 to 100 kPa (8 mil), and 8 to 120 kPa (10 mil), and drastically decrease for water pressures tending to zero. The upper limit of each range, p_{lim}, for the pipe with different thickness, identifies the threshold to which the degree of pipe roundness approaches to 1.0. Moreover, due to the elasticity of the material and in agreement with what emphasized by Rettore Neto et al. (2014), any further rise of water pressures over p_{lim}, increase the pipe diameters, even if the shape of the cross section remains circular.

According to this considerations, experimental *d(h)* data pairs where then fitted by curves of equation:

$$d = \mathrm{a} + \frac{\mathrm{b}}{p^{\mathrm{m}}} \qquad p<p_{lim} \tag{7}$$

where a, b and m are the fitting parameters. At the same time, despite the few experimental data available, linear functions were used to represent the *d(p)* relationships for $p>p_{lim}$ (Rettore Neto et al., 2014):

$$d= \mathrm{s} + \mathrm{t}\, p \qquad p>p_{lim} \tag{8}$$

with s and t fitting parameters. Table 2 shows the values of fitting parameters appearing in eqs. (7) and (8), together with the corresponding coefficients of determination. Based on the fitting curves, the effective diameters of the 6 mil pipe increased from 16.15 mm to 16.20 mm in the range of pressure 3-80 kPa, to reach the value of 16.71 mm for p=150 kPa, whereas, for the 8 mil pipe, the effective pipe diameter rose from 16.04 to 16.10 mm for 5<p<100 kPa, to reach the value d= 16.15 mm at 150 kPa; on the other side, for the 10 mil pipe, the effective diameter ranged between 15.72 and 15.85 mm for 10<p<120 kPa, and remained constant and equal to 15.85 mm, at higher p. The result evidences that, due to the rapid expansion of the cross sections occurring at low pressures, even in a range of water pressure lower than the minimum suggested by the manufacturer (p<30 kPa), the pipe effective diameters show a more limited variability than the corresponding associated to the vertical and horizontal pipe dimensions. This result is consistent with what experimentally observed by Thomson et al. (2011) on pipes with wall thicknesses ranging between 0.125 mm and 0.500 mm. These Authors evidenced that low thickness polyethylene pipes quite quickly inflate at very low water pressure reaching an almost constant cross sections, so that proposed to evaluate the pipe effective diameter according to pre-determined pressure thresholds.

Moreover, the elastic behavior of the pipe recently investigated by Rettore Neto et al. (2014), occurs only at operating pressure higher than the highest limit suggested by the manufacturer and only in pipes characterized by a very small wall thickness.

Hydrodynamic tests

Following, the results of the friction losses tests for the three considered pipes, are described. Analysis of friction losses required the preliminary evaluation of head loss in the fittings used to connect the pipes with the manometric gauges. The results of the related experiments evidenced that for all the investigated flow rates, local losses caused by the fitting connectors ranged between 92.1% and 94.8% of the measured total losses, being the remaining rate related to the friction losses in the short tram of pipe used for the tests. Fig. 9 shows, as a function of flow rate Q [l/h], the values of local head loss due to the fitting connectors, h_l [m], that include the local loss due to the enlargement (upstream connector to pipe) and subsequent contraction (pipe to downstream connector) of flow streamlines. The following quadratic fitting curve, passing from the origin of axes, was used to interpolate the experimental $h_l(Q)$ data pairs:

$$h_l = 6\times10^{-7} Q^2 + 7\times10^{-5} Q \qquad R^2=1.00 \tag{9}$$

with h_l in m and Q in l/h.

Once established the way to calculate the local losses due the fitting connectors, for each tram of the considered pipes, friction losses were evaluated and then referred to the unit pipe lengths. Fig. 10 shows the values of the measured friction loss per unit pipe length, J_{meas}, as a function of flow rates, for pipes with wall thickness of 6, 8 and 10 mil. As known, for each considered pipe, the values of J_{meas} increase at increasing Q. Moreover, for a fixed Q, the corresponding J_{meas} tends to increase according to the observed reductions of pipe diameter (fig. 8), with differences that resulted more marked at higher Q; at the same time, a certain variability of J_{meas} is still evident if considering separately the data collected on the three different pipes. Even this variability has to be associated to the recognized variations of pipe diameters with the operating pressure.

Based on the measured values of J_{meas} and Q and disposing of a procedure to determine the pipe effective diameter as a function of water pressure, the values of the Darcy-Weisbach friction factor *(f)* associated to each tram of pipe were evaluated by solving eqs. (1), in which the effective diameters were determined with eq. (7) by considering the average pressure head and neglecting their variability along the considered tram of pipe. For all the examined pipes, fig. 11 shows the experimental values of friction factor as a function of Reynolds number. Theoretical values for laminar (f=64/R for R<2000) and turbulent (f=0.302$R^{-0.25}$ for Re>2000) flow regimes are also represented. The slightly higher variability of experimental points associated to the lower R, is likely due to the incidence or the experimental errors. For the three considered pipes and in the range of investigated Reynolds numbers, the experimental f,R data pairs can be fitted by a relationship, linear in the logarithm graph, that is assumed parallel to the theoretical (eq. 2), but described by a lower coefficient c, equal to 0.285.

This result seems to conflict with that presented by Thompson et al. (2011) who, working in the range of Reynolds number between about 1,500 and 10,000 and with lay flat pipes with different wall thicknesses, obtained values of the friction factor f systematically higher and characterized by a greater variability than those obtained in the current investigation, even if differences in f values tend to decline at increasing R. In this regard, as discussed, it is noteworthy that the incidence of measurements errors increases at decreasing R. Moreover, these Authors evaluated the values of f based on pipe effective diameters measured with a caliper that are affected by relatively high experimental errors. Finally, any difference in the smoothness of pipe used in the two distinct investigations, could be partially responsible of the discrepancy observed in friction factors.

In order to determine the errors on friction loss per unit pipe length associated to the not correct estimation of the friction factor or to an inexact evaluation of pipe diameter, for all the investigated pipes, the values of J_{est} were estimated by three different methodologies and then compared to the corresponding measured. The first methodology considers a coefficient c used to evaluate the friction factors equal to c=0.285 and the empirical relationship between pipe diameter and operating pressure (eq. 7) (case A); the second takes into account the same value of c, but assumes as pipe effective diameters the value of 16.20 mm, 16.10 mm and 15.85 mm determined at $p=p_{lim}$ (case B), whereas the third considers the standard procedure, with a value of c=0.302 and the pipe diameter equal to 16.10 mm, as suggested by the manufacturer.

For the three investigated pipes, fig. 12a-c shows the values of friction losses per unit pipe length estimated in case A, case B and case C, J_{est}, as a function of the corresponding measured. As can be observed, the differences between J_{meas} and J_{est} in the three considered cases resulted more evident for the highest values of the variable. The agreement between measured and simulated values was quantified by means of the Root Mean Square Error, RMSE, that for the three considered pipes, resulted respectively equal to 0.017, 0.033 and 0.021 for case A, to 0.020, 0.049 and 0.061 for case B and finally, to 0.050, 0.058 and 0.067 for case C. This statistical parameter has been largely used (Arbat et al., 2008) and has the advantage of expressing the error in the same units as the variable, providing more information about the efficiency of the model (Alazba et al., 2012; Legates and McCabe, 1999).

The following fig. 13a-c illustrates, as a function of pressure, the errors on friction loss per unit pipe length, E, estimated in the three examined cases. Errors were evaluated as difference between estimated and measured J, expressed as percentage of the corresponding measured.

As can be observed, in case A, errors resulted generally independent of water pressure and, except that for sporadic cases mainly associated to the pipe with a wall thickness of 8 mils, they resulted lower than 5% whereas, for the other two cases, it can be noticed a certain trend with the water pressure, according to the deformation of the pipes and the consequent variation of their internal diameters. Moreover, the absolute errors associated to both cases B and C, resulted generally higher that the corresponding associated to case A. This result evidences that to improve estimation of friction losses per unit pipe length in all the range of operating pressure it is necessary to take into account the actual variations of pipe diameter and water pressure inside the pipe, as well as to consider a suitable estimation of the friction factors. On the other hand, assuming the pipe diameters suggested by the manufacturer and/or unsuitable values of the friction factor, determine inaccurate estimations of friction loss, with unavoidable consequences in the pipe design.

According to this results, for the accurate design of lay-flat polyethylene pipes, it is therefore desirable that the manufacturers provide more accurate values of pipe internal diameters, as well as their variations with the operating water pressure.

Conclusions

A comparison between two methodologies to evaluate the dimensions of lay-flat polyethylene pipes under different operating pressures was initially proposed; then, after analyzing the effects of pipe geometry on the Darcy-Weisbach friction factor, a procedure to evaluate the pipe friction loss was suggested.

Based on hydrostatic tests carried out on different pipes, characterized by wall thickness of 6 mil, 8 mil and 10 mil, it resulted that both the caliper and the photographic methods are able to detect, the variability of pipe dimensions with the operating pressure. Anyway, despite the quite similar results in terms of average pipe dimensions, the measurements carried out with the caliper were characterized by standard deviations ranging between 0.10 and 0.19 mm, higher than those associated to the more accurate photographic method that, at maximum, resulted slightly higher than 0.06 mm. The experimental measurements and the following elaborations evidenced that the pipe vertical height rapidly increases and the horizontal width decreases with hydrostatic pressures variable in the range 0-30 kPa, also confirming that the pipe cross sectional area tends to inflate quite quickly, till reaching its complete roundness. A model was then proposed to represent the effective pipe diameter as a function of water pressure, to be used to evaluate the friction loss. The model assumed the pipe cross section as constituted by two specular circle segments, with a constant wetted perimeter, in the range of water pressures lower than 80 kPa, 100 kPa and 120 kPa to which it was observed the complete roundness of the pipe cross sections. At pressure values higher than those limits instead, pipe diameter tended to increase linearly with the pressure, with a trend depending on the elasticity of the material and therefore on pipe thickness.

The results of hydrodynamic tests indicated that the friction factor can be more accurately described by using a power relationship like Blasius equation, but characterized by a coefficient c=0.285 and therefore lower than those generally used and available in the literature.

Finally, analysis of root mean square errors associated to the friction losses per unit pipe length estimated with three different procedures evidenced that, for the examined pipes, the most accurate estimation of friction loss per unit pipe length, to which corresponded the lowest RMSE values, can be obtained by considering the dependence of the effective pipe diameter by the pressure, combined with the accurate estimation of the friction factor. On the other side, by assuming a constant pipe diameter leads to a worse estimation of J, even if associated to the accurate evaluation of the friction factor. For this reason, it is therefore desirable that manufacturers provide the users with the pipe geometric data, so that in system design can be taken into account the variability of pipe diameter with the operating pressure.

Acknowledgments

The research was cofinanced by Università di Palermo (FFR 2011) and Ministero dell'Istruzione, dell'Università e della Ricerca (PRIN 2010). All the Authors setup the research and discussed the results, while V. Alagna carried out the experimental measurements and G. Provenzano wrote the paper. A special thank to the Committee for International Relations Office (CORI) of University of Palermo to support the research cooperation with the University of Valencia.

References

Alazba, A. A., Mattar, M. A., El Nesr, M. N. and Amin, M. T. 2012. Field assessment of friction head loss and friction correction factor equations. J. Irrig. Drain. Eng., 138(2), 166-176. DOI: 10.1061/(ASCE)IR.1943-4774.0000387.

Arbat, G., Puig-Bargues, J., Barragan, J., Bonany, J., and Ramirez deCartagena, F. 2008. Monitoring soil water status for micro-irrigation management versus modeling approach. Biosystems Eng., 100(2), 286–296. DOI: 10.1016/j.biosystemseng.2008.02.008.

Bagarello, V., Ferro, V., Provenzano, G., Pumo, D. 1995. Experimental study on flow resistance law for small diameter plastic pipes. J. Irrig. Drain. Eng., 121(5), 313-316. ISSN 0733-8437/85/0005/313-316.

Bagarello, V., Ferro, V., Provenzano, G., Pumo, D. 1997. Evaluating pressure losses in drip irrigation lines. J. Irrig. Drain. Eng., 123(1), 1-7. ISSN ASCE. ISSN 0733-9437197/0001-0001-0007.

Finnemore, E.J., and Franzini, J.B. 2002. Fluid mechanics with engineering applications. McGraw-Hill, Boston.

Hathoot, H.M., Al-Amound, A.T., and Mohammad, F.S. 1993. Analysis and design of trickle irrigation laterals. J. Irrig. Drain. Eng., 119(5), 756-767. DOI:10.1061/(ASCE)0733-9437(1993)119:5(756).

Humphreys, A. S., and Lauritzen, C.W. 1962. Shape factors for hydraulic design of lay-flat drip irrigation tubing. Transaction of the ASAE.

Humphreys, A. S., and Lauritzen, C.W. 1964. Hydraulic and geometrical relationships of lay-flat irrigation tubing. Agricultural Research Service. U.S. Department of Agriculture. Washington, D.C., 20402.

Juana, L., Rodriguez-Sinobas, L., and Losada, A. 2002. Determining minor head losses in drip irrigation laterals – I:Methodology. J. Irrig. Drain. Eng., 128(6), 376-384. DOI: 10.1061/(ASCE)0733-9437(2002)128:6(376).

Legates, D. R., and McCabe, J. 1999. Evaluating the use of “goodness-of fit” measures in hydrologic and hydro-climatic model validation. Water Resour. Res., 35(1), 233–241. DOI: 10.1029/1998WR900018.

Prandtl, L. 1935. The mechanics of viscous fluids. Aerodynamic Theory, (3).

Provenzano, G., and Pumo, D. 2004. Experimental analysis of local pressure losses for microirrigation laterals. J. Irrig. Drain. Eng., 130(4), 318-324. DOI:10.1061/(ASCE)0733-9437(2004)130:4(318).

Provenzano, G., Di Dio, P. M., and Leone, R. 2014. Assessing a Local Losses Evaluation Procedure for Low-Pressure Lay-Flat Drip Laterals. J. Irrig. Drain. Eng., 140(6), 04014017. DOI:10.1061/(ASCE)IR.1943-4774.0000731.

Provenzano, G., Di Dio, P.M., and Palau Salvador, G. 2007. New computation fluid dynamic procedure to estimate friction and local losses in coextruded drip laterals. J. Irrig. Drain. Eng., 133(6), 520-527. DOI:10.1061/(ASCE)0733-9437(2007)133:6(520).

Provenzano, G., Pumo, D., and Di Dio, P. M. 2005. Simplified Procedure to Evaluate Head Losses in Drip Irrigation Laterals. J. Irrig. Drain. Eng., 131(6), 525–532. ISSN 0733-9437/2005/6-525–532.

Rettore Neto, O., Botrel, T.A., Frizzone, J.A., and Camargo, A.P. 2014. Method for determining friction head loss along elastic pipes. Irrigation Science. Published online on April, 1, 2014. DOI:10.1007/s00271-014-0431-7.

Streeter V.L., and Wylie, E.B. 1985. Fluid mechanics. 8th ed. McGraw-Hill, New York.

Thompson, E., Merkley, G., Keller, A., and Barfuss, S. 2011. Experimental determination of the hydraulic properties of low-pressure, lay-flat drip irrigation systems. J. Irrig. Drain. Eng., 137(1), 37-48. DOI:10.1061/(ASCE)IR.1943-4774.0000269, 37–48.

von Karman, T. 1934. Turbulence and skin friction. 1. Aeronautical Sci., 1(1).

Von Bernuth R.D., and Wilson, T. 1989. Friction factor for small diameter plastic pipe. J. Hydr. Eng. ASCE, 115(2).