B A
S E *Biotechnol. Agron. Soc. Environ.* 2006 **10** (3), 163 – 171

Design of a micro-irrigation system based on the control volume method

Lakhdar Zella (1), Ahmed Kettab (2), Gérard Chasseriaux (3)

(1) University of Blida. BP 30 A Ouled Yaich. Blida. 09100 (Algérie). E-mail: lakhdarz@yahoo.fr
(2) National Polytechnic School. Avenue Hacen Badi, 10. El Harrach, 16200. Alger (Algérie).
(3) INH, INRA. UMR A-462 Sagah. Université d'Angers. F-49000 Angers (France).

Received 5 April 2005, accepted 24 January 2006

A micro-irrigation system design based on control volume method using the back step procedure is presented in this study. The proposed numerical method is simple and consists of delimiting an elementary volume of the lateral equipped with an emitter, called « control volume » on which the conservation equations of the fluid hydrodynamic's are applied. Control volume method is an iterative method to calculate velocity and pressure step by step throughout the micro-irrigation network based on an assumed pressure at the end of the line. A simple microcomputer program was used for the calculation and the convergence was very fast. When the average water requirement of plants was estimated, it is easy to choose the sum of the average emitter discharge as the total average flow rate of the network. The design consists of exploring an economical and efficient network to deliver uniformly the input flow rate for all emitters. This program permitted the design of a large complex network of thousands of emitters very quickly. Three subroutine programs calculate velocity and pressure at a lateral pipe and submain pipe. The control volume method has already been tested for lateral design, the results from which were validated by other methods as finite element method, so it permits to determine the optimal design for such micro-irrigation network.

Keywords. Control volume, back step method, uniformity, design, network, micro-irrigation.

Dimensionnement de système de micro-irrigation basé sur la méthode du volume de contrôle. Le dimensionnement du système de micro-irrigation basé sur la méthode du contrôle de volume et utilisant la procedure « back step » est présenté dans cette étude. La méthode numérique proposée est simple et consiste à isoler un volume élémentaire de la rampe, muni d'un goutteur et de longueur égale à l'espacement entre deux goutteurs. À ce volume de contrôle, sont appliquées les équations fondamentales de conservation relatives à l'hydrodynamique du fluide. La méthode de contrôle de volume repose sur un principe de calcul iteratif de la vitesse et de la pression, pas à pas, pour l'ensemble du réseau. À l'aide d'un simple programme informatique, les équations établies sont résolues et la convergence vers la solution est rapide. Connaissant les besoins en eau d'une culture, il est cependant aisé de choisir sur la base d'un débit moyen des goutteurs, le débit global du réseau. Ce calcul permet de repérer les dimensions économiques des conduites du réseau, assurant une uniformité de distribution d'eau acceptable (95 %). Ce programme permet de dimensionner des réseaux complexes ayant des milliers de goutteurs et offre la possibilité de choisir le réseau optimal. Il donne la vitesse et la pression en n'importe quel point du réseau. Ce programme relativement simple a été testé pour le dimensionnement de la rampe et les résultants sont similaires à ceux obtenus par la méthode des éléments finis.

Mots-clés. Contrôle du volume, back step, uniformité, dimensionnement, réseau, micro-irrigation.

1. INTRODUCTION

The finite element method (FEM) is a systematic numerical procedure that has been used to analyse the hydraulics of the lateral pipe network. A finite element computer model was developed by Bralts and Segerlind (1985) to analyse micro-irrigation submain units. The advantage of their technique included minimal computer storage and application to a large micro-irrigation network. Bralts and Edwards (1986) used a graphical technique for field evaluation of micro-irrigation submain units and compared the results with calculated data. Micro-irrigation system design was analysed using the microcomputer program by Bralts *et al.* (1991). This program provided the pressure head and flows at each emitter in the system. The program also gave several useful statistics and provided an evaluation of hydraulic design based upon simple statistics and economics criteria. Since the number of laterals in such a system is large, Bralts *et al.* (1993) proposed a technique for incorporating a virtual node structure, combining multiple emitters and lateral lines into virtual nodes. After developing these nodal equations, the FEM was used to numerically solve nodal pressure heads at all emitters. This simplification of the node number reduced the number of equations and was easy to calculate with a personal computer.

Most numerical methods for analysing micro-irrigation systems utilise the back step procedure, an iterative technique to solve for flow rates and pressure heads in a lateral line based on an assumed pressure at the end of the line. However, a micro-irrigation network program needs « large » computer memory, and a long computer calculation time due to the large matrix equations.

A mathematical model was also developed for a microcomputer by Hills and Povoa (1993) analysing hydraulic characteristics in a micro-irrigation system including emitter plugging. An iterative procedure was used to locate the average pressure using the Newton-Secant Method. Kang and Nishiyama (1994) and Kang and Nishiyama (1996a) used the finite element method to analyse the pressure head and discharge distribution along the lateral lines and submains. A golden section search was applied (Kang, Nishiyama, 1996b) to find the operating pressure heads of the lateral and submain lines corresponding to the required uniformity of water application. A computer program was developed using the back step procedure.

The primary objective of the present study is to develop and implement a simple program for the hydraulic analysis of lateral pipes and the micro-irrigation system. Using the back step procedure and control volume method (CVM), results in a non-linear system of algebraic equations, where pressure and velocity are coupled. The objective is to simultaneously solve these equations. The use of the control volume method reduced computing time required in FEM and facilitated computations.

The principal computation program was developed in Fortran language using three subroutine control volume programs; a lateral pipe program and a submain program. This computation program analysed the head pressure and discharge distribution along the lateral and submain pipes and gave total flow rate and total operating pressure of network.

2. THEORETICAL DEVELOPMENT

The proposed computation model was based upon equations of conservation of mass and energy applied to an elementary control volume, containing one emitter on one lateral or submain pipe and solved by the use of the back step procedure. The first control volume is chosen at the end of the last lateral pipe of network to find pressure at the entrance to the lateral pipe H_{Lmax}, or pressure at the end of lateral pipe H_{Lmin}. The iterative process based on the back step procedure was successively applied until the other lateral extremity and for all the network (**Figure 1**). The calculation was continued step-by-step using an iteration process for all the submain units.

Figure 1 shows the total average flow rate of network Q_{avg} in m^3·s^{-1}, which is an input for the computation, the total flow rate Q_T in m^3·s^{-1} given after computation, the total head pressure H_{Tmax} in m and the velocity V_{max} in m·s^{-1} at network entrance.

The total network is formed by the identical laterals presented in **figure 2**.

In **figure 2**, H_{Lmax} represents the pressure at lateral entrance, Q_{max} represents the total flow rate at lateral pipe entrance, V_{max} the velocity at lateral pipe entrance, H_{Lmin} the pressure at the end of lateral pipe ($L_L = L_L$), V_{Lmin} the velocity at the end of lateral pipe, $Q = q_i$ the discharge of last emitter and L_L the length of lateral pipe.

For the elementary volume (**Figure 3**), the principles of mass and energy conservation are applied. The i^{th} emitter discharge q_i in m^3·s^{-1} is assumed to be uniformly distributed along the length between emitters Δx_L, and is given by:

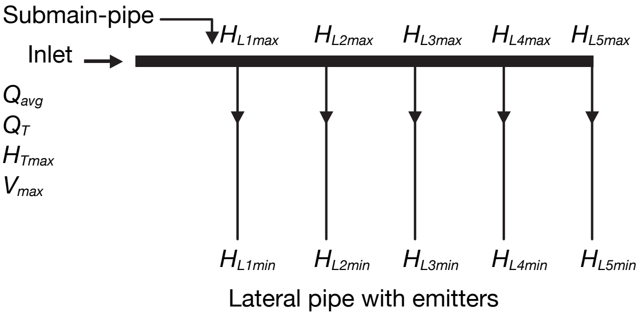

Figure 1. An example micro-irrigation network — *Exemple de réseau de micro-irrigation.*

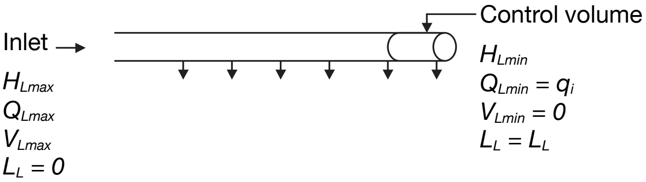

Figure 2. Micro-irrigation lateral pipe and elementary control volume — *Rampe de micro-irrigation et volume de contrôle élémentaire.*

$$q_i = \alpha \overline{H}^{\,y} \tag{1}$$

or

$$q_i = \alpha\left(\frac{H_i + H_{i+1}}{2}\right)^y \tag{2}$$

where α is an empirical constant; y is the emitter exponent; H_i, H_{i+1} respectivelly the pressure at i^{th} and $(i+1)^{th}$ point. $\overline{H}$ is the average pressure along Δx_L. The mass conservation equation for the control volume gives:

$$M_i/t = M_{i+1}/t + q_i \tag{3}$$

where M_i in kg is water mass at the entrance of the control volume, M_{i+1} in kg water mass at the exit control volume and t time in s, ($M=\rho W$; ρ is volumic mass of water, W is volume).

The energy conservation between i and $i+1$ is as follows:

$$E_i = E_{i+1} + \Delta H \tag{4}$$

where E_i is flow energy or pressure in at the input and E_{i+1} is flow energy at the exit; and ΔH including the local head loss h_f due to the emitter is the head loss in m due to friction along Δx_L. The head losses ΔH are given by the following formula:

$$\Delta H = a\overline{V_L}^{\,m} \Delta x_L \tag{5}$$

or

$$\Delta H = a\left(\frac{V_i + V_{i+1}}{2}\right)^m \Delta x_L \tag{6}$$

$\overline{V_L}$ in m·s^{-1}, is the avarage velocity between i and $(i+1)$, V_i and V_{i+1} are velocity respectively at i^{th} and $(i+1)^{th}$ cross-section lateral, the value of parameter α is given by Hazen-William equations:

for turbulent flow, R_e is Reynold's number, $R_e > 2300$,

$$a = \frac{K}{C^m A_L^{\,0,5835}} \tag{7}$$

for laminar flow, $R_e < 2300$,

$$a = \frac{32\nu}{g D_L^{\,2}} \tag{8}$$

where C is Hazen-William coefficient; K proportionable coefficient; m exponent ($m = 1$ for laminar flow, $m = 1.852$ for turbulent flow); A_L cross-sectional area of lateral pipe in m^2; D_L interior lateral pipe diameter in m; ν kinematic viscosity in m^2·s^{-1}; g gravitational acceleration in m·s^{-2}. H_L and V_L are respectively the average pressure and the average velocity between i^{th} and $(i+1)^{th}$ emitter on the lateral. The calculation model for lateral pipe solves simultaneously the system of two coupled and non-linear algebraic equations, having two unknown values: V_{i+1} and H_{i+1}.

Equations (3) and (4) become:

$$A_L V_i = A_L V_{i+1} + q_i \tag{9}$$

$$H_i + \frac{V_i^2}{2g} = H_{i+1} + \frac{V_{i+1}^2}{2g} + a\left(\frac{V_i + V_{i+1}}{2}\right)^m \Delta x \tag{10}$$

and equations (9) and (10) become:

$$V_{i+1} = V_i - \frac{\alpha}{A_L}\left(\frac{H_i + H_{i+1}}{2}\right)^y \tag{11}$$

$$H_{i+1} = H_i + \frac{1}{2g}\left(V_i^2 - V_{i+1}^2\right) - a\left(\frac{V_i + V_{i+1}}{2}\right)^m \Delta x \tag{12}$$

For the lateral, equations (11) and (12) become:

$$\left(\frac{dV}{dx}\right)_L = -\alpha \frac{\overline{H}_L^{\,y}}{A_L \Delta x_L} \tag{13}$$

$$\left(\frac{dH}{dx}\right)_L = -a\overline{V}_L^{\,m} \tag{14}$$

For submain pipe, equations system is

$$\left(\frac{dV}{dx}\right)_S = \frac{Q_S}{A_S \Delta x_s} \tag{15}$$

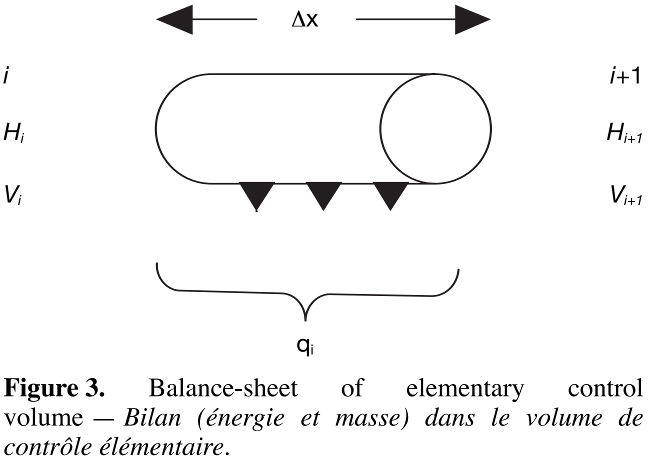

Figure 3. Balance-sheet of elementary control volume — *Bilan (énergie et masse) dans le volume de contrôle élémentaire.*

$$(\frac{dH}{dx})_S = -a\overline{V}_S^{\,m} \qquad (16)$$

where Q_s is flow rate in submain pipe, A_s a cross-sectional area of submain pipe, V_s and H_s respectively, velocity and pressure in submain pipe. At the end of the lateral $V_i = 0$, H_{Lmax} is given at entrance of lateral pipe, inlet head pressure. The slop of lateral and submain pipe are assumed null (plat level).

When H_{Lmax} is fixed, the computation program of lateral can give the distribution velocity or emitter's discharge and pressure along lateral. Theoretical development giving equations (11), (12) and (13), (14) was already solved without the use of matrix algebra through CVM or Runge Kutta presented in another paper (Zella *et al.*, 2003) and (Zella, Kettab, 2002).

2.1. Iterative procedure

The numerical calculation is accomplished using calculation program in Fortran 77 for the micro-computer. The details of the program are included in the flowchart in **figure 4**.

Step 1: to fix H_{Lmin}, $V_{Lmin} = 0$

H_{Lmin}, V_{Lmin} are respectively the pressure and the velocity at the end of lateral.

Step 2: to calculate equations system (11) and (12) or (13) and (14), so $Q_L = Q_s$ corresponding to H_{Lmin} and H_{Lmax} will be known.

Step 3: to calculate V_s using equation (15) and H_s using equation (16)

Using linear approximation, the convergence to solution is given by: H_{Lmax}, H_{smax} and V_{smax}. The test of convergence is based on the two equations (17) and (18) with ε the precision of imposed to the solution:

$$\left|\frac{\overline{H}_L - H_{L\max}}{\overline{H}_L}\right| \prec \varepsilon \qquad (17)$$

$$\left|\frac{\overline{V}_L - V_{L\max}}{\overline{V}_L}\right| \prec \varepsilon \qquad (18)$$

2.2. Uniformity calculation

The discharge of any emitter on lateral is given by typical relation equation (1), the average discharge of emitter q_{avg} is considered for all discharge emitters on lateral (NG), total discharge Q_L or Q_{max} at lateral entrance and the total average discharge $Q_{L\,avg}$ corresponding to average pressure $H_{L\,avg}$ are evaluated respectively by the following equations where q_n is the nominal emitter discharge.

$$Q_{max} = V_{Lmax}\, A \qquad (19)$$

$$Q_{Lavg} = NG.q_n \qquad (20)$$

$$q_{avg} = \frac{\sum q(i)}{NG} \qquad (21)$$

$$H_{Lavg} = \frac{\sum H(i)}{NG} \qquad (22)$$

The coefficients variation for discharge or pressure are the quotient between standard deviation and values of average emitter discharge or average pressure:

$$Cvq = \frac{\sigma_q}{q_{avg}} \qquad (23)$$

$$CvH = \frac{\sigma_H}{H_{avg}} \qquad (24)$$

The coefficient of discharge uniformity (C_{uq}) and pressure uniformity (C_{uH}) are calculated by the following (Bralts *et al.*, 1993) equations:

$$Cu_q = 100(1-C_{vq}) \qquad (25)$$

$$Cu_H = 100(1-C_{vH}) \qquad (26)$$

3. APPLICATIONS AND RESULTS

3.1. Lateral design examples

A horizontal lateral pipe (slope = 0%) of length $L_L = 250$ m and the interior diameter $D_L = 15.2$ mm. The Hazen-William coefficients of polyethylene tubing are $C = 150$, $m = 1.852$ and $K = 5.88$ and the water kinematic viscosity is $\nu = 10^{-6}$ m^2·s^{-1}. The emitter spacing Δx_L is equal to 5 m, so the number of emitter per lateral is $NG = 50$. The emitter constant and exponent are, respectively $\alpha = 9.14 \cdot 10^{-7}$, and $y = 0.5$. The required precision for the test of convergence is $\varepsilon = 10^{-6}$.

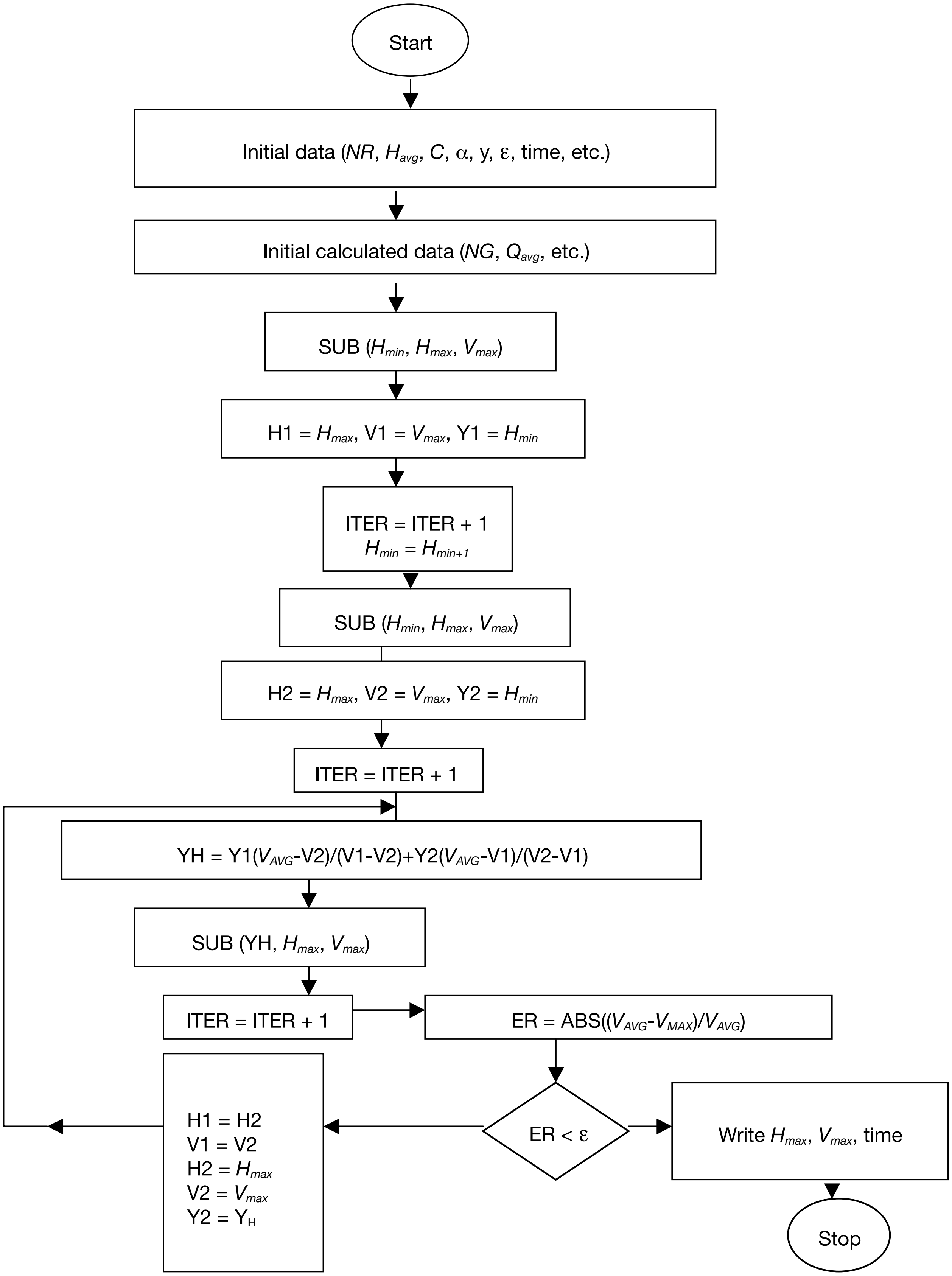

Figure 4. Flowchart of principal computation program — *Organigramme du programme principal de calcul.*

The computation program using the CVM provided the distribution of discharge and pressure with different values of head pressure, H_{Lmax} (**Table 1**). The uniformity coefficient increased with H_{Lmax} while all other parameters (diameter, length, emitter, spacing) were constant. As pressure increased from 20 to 60 m or 75% of the highest H_{Lmax}, the new uniformity coefficient, Cu_q increased only by 0.56%. This shows that it is useless to opt for the elevated H_{Lmax} values since the uniformity of distribution doesn't improve. If the increase of Cu_q is required, it is necessary to change diameter of lateral line or the type of emitters. The elevated value of H_{max} is a waste of pumping energy. Water uniformity (≈ 95%) guaranteed to satisfy water needs of plants when variation of pressure and emitter discharge were, respectively, less than 20% and 10%.

The example illustrated in **figure 5** is a result obtained by the computation program based on the CVM, the curve permits to know the pressure along the lateral line and therefore at each emitter. This results is the same as one obtained by Bralts *et al.* (1993) using the finite element method. The convergence is reached after 8 iterations and a computer time of 4 seconds compared to 3 iterations and one second for FEM and CVM, respectively. The CVM model can be considered validated by reaching the same result as the FEM model of Bralts *et al.* (1993) which was validated by the « exact » method.

3.2. Network design examples

Case 1: Simple unit submain as shown in figure 1. A horizontal submain pipe was considered (slope = 0%) with a length L_s = 50 m, a diameter D_s = 0.025 m, and a lateral number NR = 10. All the laterals are identical and their characteristics have been defined in the previous example (L_L = 250 m, $D_L = 1.52 \cdot 10^{-2}$ m). The emitters are also the same, so the total number of emitters is NGT = 500 and the calculation precision is maintained equal to $\varepsilon = 10^{-3}$.

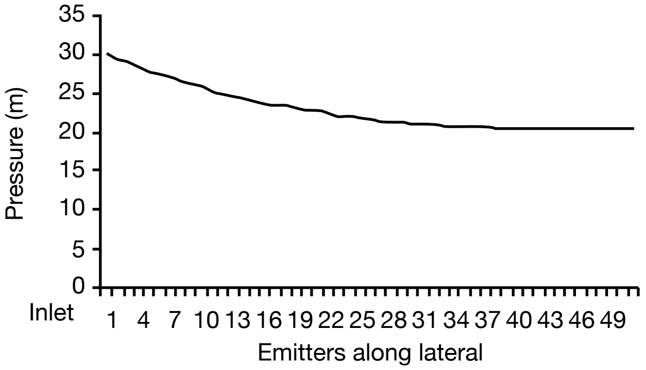

Figure 5. Pressure distribution along lateral pipe — *Distribution de la pression selon la longueur de la rampe.*

After the network program computation, the total pressure was found H_{Tmax} = 44.23 m, the maximal velocity V_{max} = 4.80 m/s, and the flow rate QT = 2.357 l/s.

These results of the network program were verified by the execution of the lateral program for the 10 laterals network. For the 10th lateral, fixed to the extremity of submain pipe, the total flow rate was $Q_L = 0.2172 \cdot 10^{-3}$ l·s^{-1} for input pressure H_{Lmax} = 30 m, **Figure 5** represents the distribution of the pressure along lateral pipe. Between the 10th and the 9th lateral, the pressure loss was determined by the Darcy-Weisbach equation as ΔH_s = 0.062 m. The calculation is achieved for the ten laterals and results are regrouped in **table 2**. The difference between the average flow rate Q_{avg} project and the total flow rate, Q_T, given after computation was only $3.9 \cdot 10^{-3}$ l/s. It means Q_{avg} introduced by designer data was completely distributed for all emitters.

Water and mineral elements are delivered to a localised place, to the level of each plant by the emitters whose discharge is function of lateral pressure. The precision of irrigation application, which must exactly satisfy the requirement for cultivation, depends fundamentally on the design of the network. It takes into account the pressure variations, which are due not only to head loss in the pipes of network but also to the land slope, characteristics of emitter, water and

Table 1. Results of lateral design, testing some H_{Lmax} — *Résultats relatifs au dimensionnement de la rampe, avec plusieurs valeurs de* H_{Lmax}.

H_{Lmax} (m)	H_{L1} (m)	$q_{1(max)}$ (10^{-3} cm^3·s^{-1})	$H_{L50\,(min)}$ (m)	$q_{50\,(min)}$ (10^{-3} cm^3·s^{-1})	Cu_q (%)	Cu_H (%)	iter.
20	19.61	0.40	13.39	0.33	94.05	87.80	4
25	24.52	0.42	16.84	0.37	94.15	88.00	4
30	29.43	0.49	20.30	0.41	94.22	88.15	3
40	39.25	0.57	27.27	0.47	94.34	88.39	4
50	49.07	0.64	34.29	0.53	94.42	88.58	5
60	58.90	0.70	41.33	0.58	94.50	88.72	5
80	78.56	0.81	55.51	0.68	94.61	88.95	5

Table 2. Design results by lateral program — *Résultats du dimensionnement des rampes.*

N° lateral	H_{Lmax} (m)	H_{Lmin} (m)	ΔH_s (m)	Q_L (10^{-2} l·s^{-1})	Q_s (10^{-2} l·s^{-1})	Cu_q (%)
10	30.00	20.30	0.06	21.72	21.72	94.22
9	30.06	20.34	0.23	21.74	43.50	94.22
8	30.29	20.50	0.48	21.82	65.33	94.22
7	30.78	20.84	0.80	22.00	87.33	94.23
6	31.58	21.40	1.18	22.29	109.63	94.24
5	32.77	22.23	1.63	22.72	132.35	94.26
4	34.41	23.37	2.13	23.93	155.65	94.28
3	36.55	24.86	2.70	24.02	179.67	94.30
2	39.25	26.74	3.32	24.90	204.57	94.33
1	42.58	29.08	-	25.96	230.54	94.36
Total			**12.58**	**230.54**	**230.54**	**94.26**$_{\text{avg}}$

air temperature and the possible plugging of emitter orifice.

Case 2: Inlet flow rate at middle of submain. The network (**Figure 6**) was composed with 2 symmetric submain pipes with the same data as case 1. $H_{Tmax} = 36.147$ m, $V_{max} = 2.40$ m/s, $Q_T = 2.356$ l/s.

The network program is tested for this case of micro-irrigation network. Results were correct and precise at entrance of the submain pipe. The average flow rate, Q_{avg}, was distributed completely between emitters, assuring zero velocity to the extremity of every lateral pipe and a superior distribution uniformity to 94.22%. The difference between the average flow rate of project Q_{avg} and Q_T, given after computation is only $3.9 \cdot 10^{-3}$ l·s^{-1}. Results are essentially instantaneously given and the computer time was very short.

Case 3: A network as described in Figure 1 with the same data. The results after computation are shown for several NR ($L_s = 50$ m) in **table 3**.

For $NR = 50$ and $NR = 100$, submain diameter is 0.08 m, because with $D_s = 0.025$ m there is no solution, the flow rate is high exciting a very important head losses in submain and laterals. In these cases, velocities are very high and it's necessarily to increase more submain diameter in order to obtain value around 1.5 m·s^{-1}.

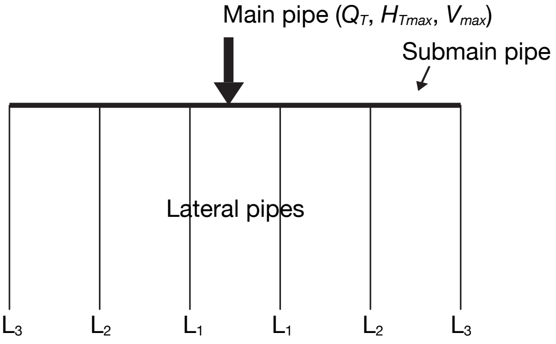

Figure 6. Network framework, case 2 — *Schéma du réseau, cas n° 2.*

These results show that the computer program operates well and converges quickly toward fixed (Q_{avg}) solution at the desired uniformity. The uniformity of emitters distribution is superior to 94.22% for these tested cases. The program gave some precise results for networks covering an irrigated area of 12.5 ha totalling 5000 emitters. In order to analyse such a large micro-irrigation system accurately and efficiently, the task of calculating the pressure and discharges for each emitter becomes enormous so it's important to choose this computation method.

4. CONCLUSION

The control volume method was tested and validated for the lateral design and was used in this paper for designing a simple micro-irrigation network. The model precisely describes the distribution of pressure and discharges to all network emitters. In this case, the total discharge and the total required pressure, the uniformity of pressure and discharges are determined for each pattern of design. The combination of size network pipes and uniformity distribution (plants water requirement) is applied to guarantee an optimal exploitation taking into account the limits imposed by the specific norms for micro-irrigation and the technical limits of velocity and pressure tolerance. Uniformity of water distribution is a main criterion for network design. A microcomputer program was developed that permits designs of high precision in order to optimise the water distribution uniformity at a reasonable investment cost. The proposed methodology is computationally efficient and can help irrigation consultants in the design of micro-irrigation system. In arid and semiarid regions, design is important to increase yields and to conserve water and soil as well as the economical utilisation of power.

Table 3. Design results (case 3) — *Résultats du dimensionnement du réseau n° 3.*

NR	**NGT**	**area irrigated** (ha)	H_{Tmax} (m)	V_{max} ($m \cdot s^{-1}$)	Q_T (10^{-2} $l \cdot s^{-1}$)	Cu_q (%)
5	250	0.625	36.14	2.40	117	94.0
10	500	1.250	44.23	4.80	235	94.5
20	1000	2.500	44.23	4.80	470	95.0
50	2500	6.200	38.57	2.34	1175	96.0
100	5000	12.500	59.53	4.70	2361	96.0

Notations

α: empirical constant of emitter
ν: kinematic viscosity of water ($m^2 \cdot s^{-1}$)
ε: precision of convergence (%)
σ: standard deviation of average discharge emitter (%)
ΔH: head loss along the length of control volume Δx (m)
ΔH_L: head loss along the length lateral pipe (L_L) (m)
ΔH_S: head loss along the length submain pipe (L_s) (m)
Δx_L: spacing between emitters (m)
Δx_S : spacing between laterals (m)
α: coefficient of head loss (Hazen-William)
A_L: cross-sectional area lateral pipe, m^2
A_s: cross-sectional area submain pipe, m^2
C: Hazen-William coefficient
Cu_H: coefficient of pressure uniformity at the lateral pipe (%)
Cu_q: coefficient of discharge uniformity at the lateral pipe (%)
C_{vH}: coefficient of variation of pressure emitter (%)
C_{vq}: coefficient of variation of discharge emitter (%)
D_L: interior lateral pipe diameter (m)
D_s: interior diameter of submain pipe (m)
E_i: water energy at entrance of control volume (m)
E_{i+1}: water energy at exit of control volume (m)
g: gravitational acceleration ($m \cdot s^{-2}$)
H_{L1}: pressure of emitter number 1 at the lateral ($\approx H_{Lmax}$) (m)
H_{L50}: pressure of emitter number 50 at the lateral ($= H_{Lmin}$) (m)
H_{Lavg}: average pressure at lateral in m corresponding to average discharge Q_{Lavg} ($m^3 \cdot s^{-1}$)
H_{Lmax}: pressure at the entrance to the lateral pipe (m)
H_{Lmin}: pressure at the end of the lateral pipe (m)
H_s: pressure in submain pipe (m)
H_{smax}: pressure at the entrance submain pipe (m)
H_{Tmax}: the total pressure of the network (m)
Iter: number of computation iteration
K: coefficient of proportionality
L_L: the length of the lateral pipe (m)
L_s: length of submain pipe, m
m: exponent of regime flow
M_i: water mass at the entrance of control volume (kg)
M_{i+1}: water mass at exit of control volume (kg)
NG: number of emitters on lateral
NGT: total number of emitter of network
NR: number of lateral pipe of network
q_{avg}: average discharge of emitters ($m^3 \cdot s^{-1}$)
Q_{avg}: the total average flow rate of the network, input data ($m^3 \cdot s^{-1}$)
q_i: the discharge of emitter i ($m^3 \cdot s^{-1}$)
Q_{max} (= Q_L): the total flow rate at the lateral entrance ($m^3 \cdot s^{-1}$)
q_n: nominal discharge of emitter ($m^3 \cdot s^{-1}$)
Q_s: flow rate in submain ($m^3 \cdot s^{-1}$)
Q_T: the total average flow rate of the network given by computation, output data ($m^3 \cdot s^{-1}$)
R_e: Reynolds number
t: time (s)
V_{Lmax}: the velocity at the lateral pipe entrance ($m \cdot s^{-1}$)
V_{Lmin}: the velocity at the end of the lateral pipe ($m \cdot s^{-1}$)
V_{max}: the velocity at the network entrance ($m \cdot s^{-1}$)
V_s: velocity in submain ($m \cdot s^{-1}$)
V_{smax}: velocity at the entrance submain pipe ($m \cdot s^{-1}$)
y: emitter exponent

Bibliography

Bralts VF., Segerlind LJ. (1985). Finite element analysis of drip irrigation submain units. *Trans. Am. Soc. Agric. Eng.* **28** (3), p. 809–814.

Bralts VF., Edwards DM. (1986). Field evaluation of submain units. *Trans. Am. Soc. Agric. Eng.* **29** (6), p. 1659–1664.

Bralts VF., Shayya WH., Driscoll MA., Cao L. (1991). *An expert system for the hydraulic design of microirrigation systems. International Summer Meeting, ASAE, New Mexico*, paper n° 91-2153, 12 p.

Bralts VF., Kelly SF., Shayya WH., Segerlind LJ. (1993). Finite element analysis of microirrigation hydraulics using a virtual emitter system. *Trans. Am. Soc. Agric. Eng.* **36** (3), p. 717–725.

Hills DJ., Povoa AF. (1993). *Pressure sensivity to microirrigation emitter plugging. International Summer Meeting*, ASAE/CSAE, Washington. Paper n° 93-2130, 17 p.

Kang Y., Nishiyama S. (1994). Finite element method analysis of microirrigation system pressure distribution. *Trans. Jap. Soc. Irrig. Drain. Reclam. Eng.* **169**, p. 19–26.

Kang Y., Nishiyama S. (1996a). Analysis and design of microirrigation laterals. *J. Irrig. Drain. Eng.* **122** (2), march/april, ASCE, p. 75–82.

Kang Y., Nishiyama S. (1996b). Design of microirrigation submain units. *J. Irrig. Drain. Eng.* **122** (2), march/april, ASCE. p. 83–90.

Zella L., Kettab A. (2002). Numerical methods of microirrigation lateral design. *Biotechnol. Agron. Soc. Environ.* **6** (4), p. 231–235.

Zella L., Kettab A., Chasseriaux G. (2003). Hydraulic simulation of micro-irrigation lateral using control volume method. *Agronomie* **23** (1), p. 37–44.

(10 ref.)