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Development of Equations for calculating the Head Loss in Effluent Filtration in Microirrigation Systems using Dimensional Analysis

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Several equations for calculating the head loss in disc, screen and sand filters when using effluents have been developed by means of dimensional analysis. The variables considered in the equations, other than head loss, were filtration level, filtration area, water density and viscosity, mean diameter of the particle size distribution of the effluent, volume and flow rate across the filter and concentration of suspended solids in the effluent. These nine variables were incorporated into six dimensionless groups obtained through Buckingham's method. Experiments to analyse head losses across filters were carried out using five effluents with 115, 130 and 200 μm disc filters, 98, 115, 130 and 178 μm screen filters and a sand filter with an effective grain size of 0·65 mm. The equations were satisfactorily adjusted with experimental data. However, both effluent and type of filter influenced the adjustments.

1. Introduction

In many problems of hydraulic engineering, with the exception of hydrostatic and laminar flow problems, the available analytical tools are not capable of finding precise enough solutions. When turbulent flow problems are numerically manageable, the solutions are only a first approach and it is often necessary to verify and adjust them through experimentation. In this empirical phase, it is important to use dimensional analysis and dimensionless parameters.

When dimensional analysis is applied to studying a physical phenomenon that depends on m independent parameters, it is possible to find an equivalent equation for this phenomenon that is only a function of $m-r$ dimensionless independent parameters (r being the phenomenon dimensional matrix range). This reduction of parameters considerably simplifies the experiments that must be carried out. Buckingham's theorem, or Π group theorem (Buckingham, 1915), and Rayleigh's method are both useful for obtaining the dimensionless groups involved in the phenomenon. The procedure consists of substituting an unknown function of m variables with another unknown function of $m-r$ dimensionless variables. Knowledge about this function must be obtained in an experimental way (Langhaar, 1951; Allen, 1952; Ipsen, 1960; US Department of Interior, 1980).

In pressurised irrigation systems, the flow through the filtration systems is very complex because of the specific filter design characteristics, limiting the flow and is further dependent on the properties of the circulating water. This complexity is increased when effluents are used in irrigation due to the increased risk of clogging.

The equations available to describe the operation of filters used in microirrigation systems were developed mainly for screen and sand filters, not for the most recent disc filters. Equations used traditionally to study filtration require the use of parameters related to filtration cake characteristics which are difficult to estimate because of variations that occur during any filtration cycle (Adin & Alon, 1986; McCabe *et al.*, 2001). Dimensionless analysis and dimensionless parameters are useful tools for the analysis of this type of

Notation

A	total filtration surface, m^2		m	number of variables
a, b, c, d, e	empirical exponents		Q	filtered liquid flow rate, m^3 s^{-1}
			r	dimensional matrix range
C	suspended solids concentration, kg m^{-3}		T	time
D_e	effective grain size of the sand used in the filter, m		V	filtered liquid volume, m^3
			ΔH	head loss across the filter, Pa
D_p	mean diameter of particle size distribution, m		μ	water viscosity, Pa s
f, g	functions		ρ	water density, kg m^{-3}
k	empirical coefficient		Π	dimensionless group
L	length		ϕ_f	filtration level, m
M	mass			

hydraulic problem. Thus, Arnó (1990) used this technique with screen filters and uniform size particles and obtained two dimensionless groups that characterised the filtration process.

The main objectives of this paper are, first, to determine the usefulness of dimensional analysis to study the filtration of effluents in drip irrigation systems and, second, to find equations capable of describing filter clogging through dimensionless groups.

2. Materials and methods

2.1. *Obtaining dimensionless groups*

Filter clogging can be determined by looking at the progressive increase of head loss caused in the filter by the flow of water. Several variables having some influence on head loss across the filter have been previously identified (Adin & Alon, 1986; Zeier & Hills, 1987; Arnó, 1990). Standing out among these variables are filtration level, flow rate across the filter, volume of filtered water, filtration surface, suspended solids in water, mean diameter of suspended particles and water viscosity and density.

Considering these variables, the following relationship can be established:

$$f\left(\Delta H, \phi_f, D_p, A, Q, C, V, \mu, \rho\right) = 0 \qquad (1)$$

where ΔH is the total head loss across the filter in Pa; ϕ_f is the filtration level or filter pore in m; D_p is the mean diameter of effluent particle size distribution in m; A is the total filtration surface in m^2; Q is the flow rate across the filter in m^3 s^{-1}; C is the concentration of total suspended solids in the filter influent in kg m^{-3}; V is the water volume across the filter in m^3; μ is the water viscosity in Pa s; and ρ is the water density in kg m^{-3}.

For the sand filter, the filtration level was replaced by the effective grain size D_e of the sand filling the filter. The effective grain size is the screen pore that retains 90% of the sand mass.

Considering all the variables ($m = 9$) and their dimensions of length (L), mass (M) and time (T), the resulting dimensional matrix was

	ΔH	ϕ_f	D_p	A	Q	C	V	μ	ρ
L	−1	1	1	2	3	−3	3	−1	−3
M	1	0	0	0	0	1	0	1	1
T	−2	0	0	0	−1	0	0	−1	0

The range of the phenomenon dimensional matrix was $r = 3$. Thus, there must be $9 - 3 = 6$ Π dimensionless groups that could explain the filter clogging. The Π groups obtained applying Buckingham's method were

$$\Pi_1 = \left(\frac{\Delta H^{1/4}\phi_f}{C^{1/4}Q^{1/2}}\right) \qquad (2)$$

$$\Pi_2 = \left(\frac{\Delta H^{1/4}D_p}{C^{1/4}Q^{1/2}}\right) \qquad (3)$$

$$\Pi_3 = \left(\frac{\Delta H^{3/4}V}{C^{3/4}Q^{3/2}}\right) \qquad (4)$$

$$\Pi_4 = \left(\frac{\Delta H^{1/2}A}{C^{1/2}Q}\right) \qquad (5)$$

$$\Pi_5 = \left(\frac{\mu}{\Delta H^{1/4}Q^{1/2}C^{3/4}}\right) \qquad (6)$$

$$\Pi_6 = \left(\frac{\rho}{C}\right) \qquad (7)$$

Taking into account these six Π dimensionless groups, Eqn (1) can be expressed with the following function:

$$g(\Pi_1, \Pi_2, \Pi_3, \Pi_4 \Pi_5, \Pi_6) = 0 \tag{8}$$

Applying Eqn (8), the following potential equation was found:

$$\frac{\mu}{\Delta H^{1/4} Q^{1/2} C^{3/4}} = k\left(\frac{\Delta H^{3/4} V}{C^{3/4} Q^{3/2}}\right)^a \left(\frac{\Delta H^{1/2} A}{C^{1/2} Q}\right)^b \times \left(\frac{\Delta H^{1/4} \phi_f}{C^{1/4} Q^{1/2}}\right)^c \left(\frac{\Delta H^{1/4} D_p}{C^{1/4} Q^{1/2}}\right)^d \times \left(\frac{\rho}{C}\right)^e \tag{9}$$

where k is an empirical coefficient and a, b, c, d and e are empirical exponents.

Even though the six dimensionless groups that were found in Eqn (9), other equations were obtained by not considering or changing some of the dimensionless groups.

2.2. *Experimental test of the relationships among dimensionless groups*

In order to check the validity of Eqn (9) with the dimensionless groups involved in the filtration phenomenon, tests were carried out with five different effluents. Effluent 1 was wastewater from a meat industry. Effluents after secondary treatment through a sludge process in the wastewater treatment plants (WWTP) of Girona and Castell-Platja d'Aro (Spain) were effluents 2 and 3, respectively. Effluent 4 was effluent 2 filtered through a sand filter with an effective grain size of 0·65 mm and a uniformity coefficient (the ratio between the screen openings that retain 40% and 90% of the sand, respectively) of 1·3. Finally, effluent 5 was effluent 3 after filtration through sand with an effective grain size of 0·45 mm and a uniformity coefficient of 1·6, and disinfection by exposition to ultraviolet light and chlorination.

Before entering the filter, effluents were sampled periodically to determine the level of total suspended solids (TSS). In addition, the mean diameter of particle size distribution D_p was measured with a Galai Cis1 particle laser analyser (Galai Production Inc., Israel). The average and standard deviation values of these two parameters of the different effluents used in filtration tests are shown in Table 1.

Three common filter types used in microirrigation systems (screen, disc and sand) were tested. The main characteristics of the filters used in the experiments, as well as the effluents tested with each filter are shown in Table 2. The sand filter used with effluents 1 and 2 was filled with 175 kg of sand with an effective grain size and uniformity coefficient of 0·65 mm and 1·3, respectively, as a single filtration layer. Diagrams of the experimental arrangements used in the trials with the different effluents are shown in *Fig. 1*.

Experiments consisted of determining the head loss and the water volume across the filter at regular time intervals until a maximum head loss of 49 kPa was

Table 1
Average and standard deviation of physical parameters of the effluents used

Parameter	*Effluent 1*	*Effluent 2*	*Effluent 3*	*Effluent 4*	*Effluent 5*
Total suspended solids (TSS), g m^{-3}	176 ± 24·8	24·4 ± 14·7	10·6 ± 3·42	8·61 ± 3·94	4·93 ± 1·24
Mean size particle distribution diameter, μm	9·85 ± 6·80	8·78 ± 8·74	3·66 ± 1·65	8·19 ± 3·37	3·39 ± 1·14

Table 2
Main characteristics of the tested filters and effluents used

Filter type	*Filter*	*Filtration level, μm*	*Diameter, mm*	*Filtration surface, cm²*	*Effluents tested*
Disc	D115	115	50·8	953	1, 2 and 4
	D130	130	50·8	953	1, 2, 3 and 4
	D200	200	50·8	953	1, 2 and 4
Screen	S98	98	50·8	946	1, 2 and 4
	S115	115	50·8	946	1, 2 and 4
	S130	130	50·8	640	3 and 5
	S178	178	50·8	946	1, 2 and 4
Sand	Sand	650*	508	1963	1 and 2

*Effective grain size.

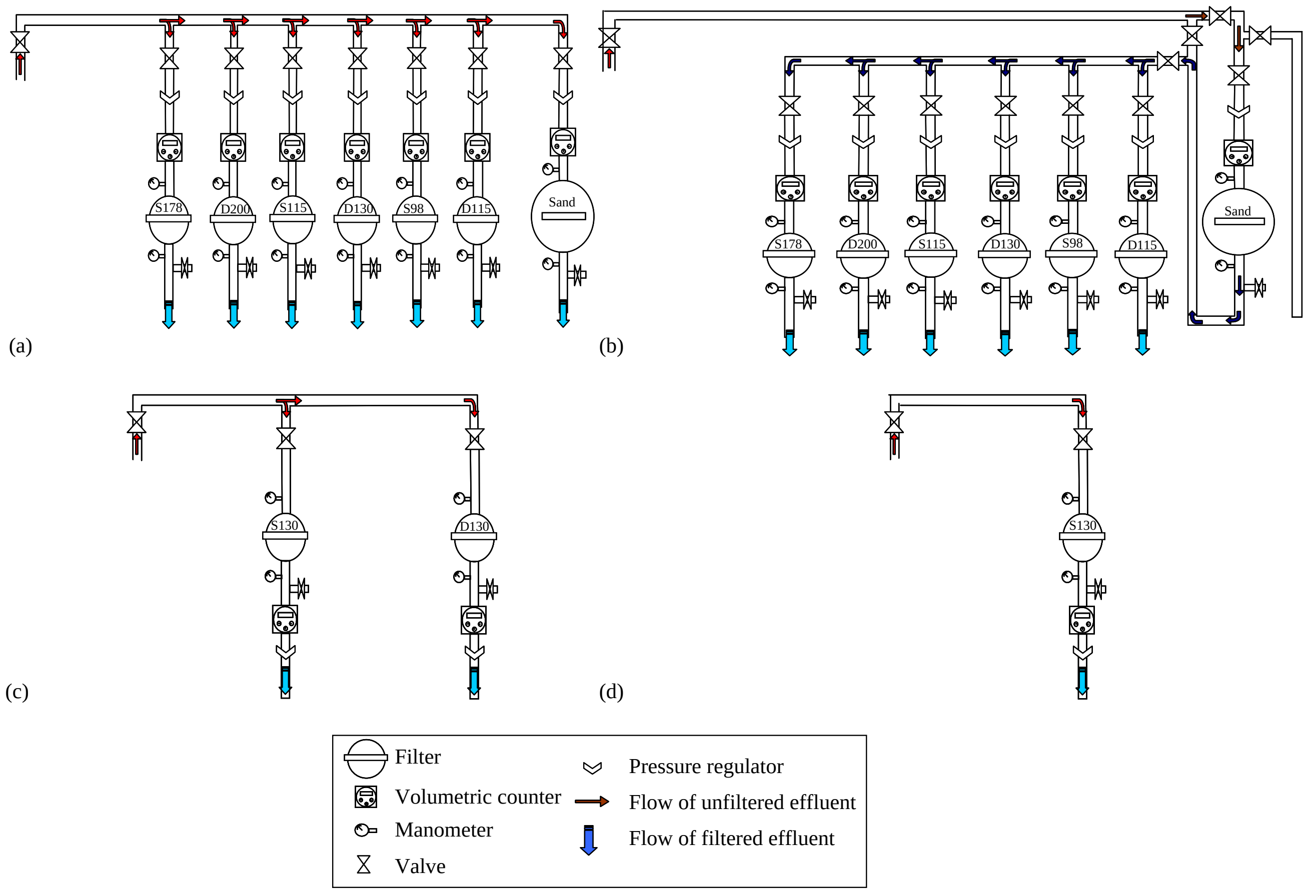

Fig. 1. Working diagram of the filtration bank with the different effluents (a) Effluents 1 and 2; (b) Effluent 4; (c) Effluent 3; (d) Effluent 5

Table 3
Mean filtration flow rate and standard deviations for the different filters and effluents during the experiments

Filter	*Mean filtration flow rate, l s^{-1}*				
	Effluent 1	*Effluent 2*	*Effluent 3*	*Effluent 4*	*Effluent 5*
D115	$1{\cdot}10 \pm 0{\cdot}58$	$0{\cdot}45 \pm 0{\cdot}23$	–	$0{\cdot}13 \pm 0{\cdot}00$	–
D130	$0{\cdot}74 \pm 0{\cdot}53$	$0{\cdot}53 \pm 0{\cdot}29$	$0{\cdot}29 \pm 0{\cdot}01$	$0{\cdot}13 \pm 0{\cdot}01$	–
D200	$0{\cdot}69 \pm 0{\cdot}53$	$0{\cdot}61 \pm 0{\cdot}02$	–	$0{\cdot}12 \pm 0{\cdot}01$	–
S98	$1{\cdot}53 \pm 0{\cdot}48$	$0{\cdot}25 \pm 0{\cdot}09$	–	$0{\cdot}09 \pm 0{\cdot}00$	–
S115	$1{\cdot}06 \pm 0{\cdot}81$	$0{\cdot}30 \pm 0{\cdot}28$	–	$0{\cdot}09 \pm 0{\cdot}01$	–
S130	–	–	$0{\cdot}29 \pm 0{\cdot}02$	–	$0{\cdot}33 \pm 0{\cdot}01$
S178	$0{\cdot}64 \pm 0{\cdot}38$	$0{\cdot}51 \pm 0{\cdot}23$	–	$0{\cdot}09 \pm 0{\cdot}00$	–
Sand	$0{\cdot}76 \pm 0{\cdot}48$	$0{\cdot}57 \pm 0{\cdot}05$	–	–	–

D115, D130 and D200, 115 μm, 130 μm and 200 μm disc filters; S98, S115, S130 and S178, 98 μm, 115 μm, 130 μm and 178 μm screen filters.

reached. The head loss was measured by using two filled manometers at the filter inlet and outlet, respectively. The volume of filtered effluent was determined by means of a volumetric counter. Instantaneous flow was computed using the effluent volume and the experiment time. The mean and standard deviation values of the filtration flow rate are shown in Table 3. Values of $0{\cdot}001$ Pa s and 998 kg m^{-3} were used for water viscosity and density, respectively, at a reference temperature of 20 °C (Lide, 1995).

With effluent 1, seven experiments were carried out for each screen and disc filter, while three were carried out with the sand filter. With effluent 2, each screen and disc filter was tested six times, while head loss trials were carried out 21 times with sand filter. With effluent 4, each screen and disc filter was tested five times. Finally, screen filters were tested five times while disc filters were tested four times when using effluents 3 and 5.

2.3. *Statistical treatment of data*

Data obtained at regular intervals from the filtration trials allowed the different dimensionless groups to be computed. The groups were statistically adjusted with the developed equations by means of the regression procedure (REG) of the SAS statistical package (SAS, 1999).

3. Results and discussion

3.1. *Performance of the developed equations*

Table 4 shows the results of the regression coefficients, the significance levels and the variation coefficients of the adjustments for each individual filter and for all the screen filters, all the disc filters and all the filters considered together in function of the different effluents that were used in the experiments. Although the regression coefficients are sometimes not very high, in most of the cases the adjustments are significant with a probability $P<0{\cdot}001$.

The results of the regressions (Table 4) vary with the type of filter and effluent. The effects of both the filter and effluent are important, because adjustments to equations with the same filter show important differences with regard to the effluent used, and looking at only one effluent, the equations fit differently for each filter. Every effluent has different types of particles with different physical and chemical properties which affect the retention of the particles (Lawler, 1997). Besides, when biological particles are retained in the filter media and pressure increases, these particles can be deformed and can pass through the filter (Adin & Alon, 1986) affecting the head loss across the filter. On the other hand, Ravina *et al.* (1997) found that differences in filters' performances when using effluents were associated mainly to the type of filtering element and to some extent to hydraulic and other specific characteristics of the filter design.

Despite testing other potential equations with less dimensional numbers than Eqn (9), the regression coefficients are lower than those obtained with Eqn (9), the equation that incorporated all the Π dimensionless groups. As theoretical values of density and viscosity are considered, the different equations use the same values of these two parameters. If data on viscosity and density of different effluents had been recorded, the adjustments could have been more representative of each working condition.

The adjustment carried out with all the data of all the filters and all the effluents produces an adjusted coefficient of determination of 0·882. The numerical value of this coefficient has a high level of significance indicating that with a single equation is feasible to calculate the head losses caused by different effluents in several types of filters. However, when the results of all the filters and the effluents are considered, the goodness of fit increases because the regression was made with a larger amount of data and there was a partial correction of the adjustment error. In this way, the applicability of Eqn (9) is potentially reduced because, despite obtaining a generic equation, it describes the performance of screen, disc and sand filters, when these different types of filters all behave differently. When an attempt was made to apply the resultant equation, no logical values were obtained, due to the effect of the compensation of experimental data.

In this respect, it seems more appropriate to consider as valid an equation like Eqn (9) that at least takes into consideration the type of filter (disc, screen or sand) for all the effluents. In any case, the resultant equations must be considered as a guide due to the important effect of the effluent on head loss across the filter. Since adjusting the equations for each filter and effluent results in a high number of separate equations, it is useful to give a global equation for each filter type.

Equation (9) has been correlated with all the data for all the effluents and for each type of filter, yielding the different coefficients and exponents shown in Table 5.

There are very few models for studying head loss in microirrigation system filters. Zeier and Hills (1987) developed an equation for estimating head loss in screen filters. However, the variables were not the same and it has been impossible to compare the results obtained by Zeier and Hills with those from the equations developed.

3.2. *Applications*

In this section, different applications of the developed equations are shown.

3.2.1. *Calculation of the head loss across the filter*

An effluent with a concentration of total suspended solids of $35\,\mathrm{g\,m^{-3}}$ and a mean particle diameter of

Table 4
Adjusted coefficient of determination R^2adj, variation coefficient C_v and number of observations N of Eqn (9) tested for all the filters and types of filters related with the effluents

Filter	*Effluent*	*Number of observations (N)*	*Adjusted coefficient of determination (R^2 adj)*	*Coefficient of variation (C_v), %*
D115	1	77	0·965***	−4·63
	2	126	0·933***	−16·1
	4	49	0·614***	90·1
	1, 2 and 4	252	0·742***	−49·4
D130	1	82	0·543***	26·2
	2	130	0·801***	9·10
	3	80	0·392***	3.36
	4	194	0·719***	4.24
	1, 2, 3 and 4	486	0·731***	12·3
D200	1	288	0·794***	13·4
	2	129	0·702***	6·01
	4	114	0·170***	2·82
	1, 2 and 4	531	0·920***	14.5
All disc	1	447	0·935***	41·3
	2	385	0·981***	18·6
	4	243	0·991***	4·60
	1, 2, 3 and 4	1269	0·937***	28·6
S98	1	100	0·633***	20·5
	2	124	0·713***	6·00
	4	162	0·055***	3·72
	1, 2 and 4	386	0.871***	14·6
S115	1	167	0·576***	51·4
	2	189	0·888***	6·87
	4	84	0·576***	3·63
	1, 2 and 4	440	0·915***	11·6
S130	3	195	0·665***	5·92
	5	191	0·684***	5·84
	3 and 5	386	0·637***	6·29
S178	1	198	0·816***	11·4
	2	96	0·969***	2·35
	4	52	0·429***	4·80
	1, 2 and 4	346	0·897***	15·5
All screen	1	465	0·525***	21·7
	2	409	0·899***	6·75
	4	298	0·035***	4·37
	1, 2, 3, 4 and 5	1558	0·852***	14·8
Sand	1	171	0·975***	3·45
	2	161	0·866***	2·96
	1 and 2	332	0·843***	4·82
All	1	1083	0·866***	32·4
	2	955	0·935***	13·4
	3	541	0·976***	4·77
	4	389	0·508***	7·46
	1, 2, 3, 4 and 5	3159	0·882***	22·3

D115, D130 and D200, 115 μm, 130 μm and 200 μm disc filters; S98, S115, S130 and S178, 98 μm, 115 μm, 130 μm and 178 μm screen filters.
***Probability $P<0.001$.

7·2 μm is filtered with a flow rate of $12\,m^3\,h^{-1}$ in disc filters with a filtration level of 115, 130 and 200 μm, respectively, and a filtration surface of $953\,cm^2$. If water density is $998\,kg\,m^{-3}$ and water viscosity is 0·001 Pa s, the development of the head loss across the filter with the filtered volume could be analysed.

Table 5
Values of coefficient and exponents of Eqn (9) for disc, screen and sand filters

Filter type	*Coefficient k*	*Exponents*				
		a	*b*	*c*	*d*	*e*
Disc	$4{\cdot}81 \times 10^{-6}$	−0·21	0·67	0·65	−0·12	0·67
Screen	$1{\cdot}10 \times 10^{-6}$	−0·17	0·74	0·72	−0·19	0·61
Sand	$8{\cdot}61 \times 10^{-8}$	−0·14	0·81	0·69	−0·18	0·52

Applying Eqn (9) with the appropriate empirical factors for disc filters shown in Table 5 and substituting the known variables for the 115 μm disc filter gives

$$\frac{0{\cdot}214}{\Delta H^{1/4}} = 4{\cdot}81 \times 10^{-6}\left(64214\Delta H^{3/4} V\right)^{-0{\cdot}21}\left(152{\cdot}82\Delta H^{1/2}\right)^{0{\cdot}67} \times\left(0{\cdot}005\Delta H^{1/4}\right)^{0{\cdot}65}\left(2.8 \times 10^{-4}\Delta H^{1/4}\right)^{-0{\cdot}12} \times(28514)^{0{\cdot}67} \quad (10)$$

Using the same procedure with the other disc filters, the head loss can then be calculated for each filtered volume. Results are depicted in *Fig. 2*, where it can be seen that the higher the filter pore, the lower the head loss with the same effluent, as reported in Adin and Alon (1986).

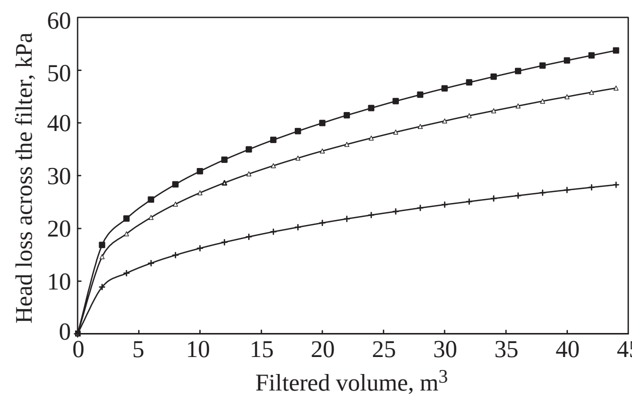

Fig. 2. Head loss across 115 μm —■—, 130 μm —△—and 200 μm —|— disc filters with respect to the filtered volume of an effluent with 35 g TSS m^{-3} and a mean particle diameter of 7·2 μm; filtration surface of each filter is 953 cm^2 and the filtration rate is 12 m^3 h^{-1}; TSS, total suspended solids

3.2.2. *Calculation of the filtered volume with different types of filters*

The flow rate of an effluent used in a drip irrigation system is 2 m^3 h^{-1}. This effluent has 55 g m^{-3} of total suspended solids, a mean particle size of 9·1 μm, a density of 998 kg m^{-3} and a viscosity of 0·001 Pa s. Determine the filtered volume for a head loss of 49 kPa with the following filters: (1) a 130 μm screen filter of 50·8 mm in diameter and a filtration surface of 946 cm^2; and (2) a sand filter with an effective grain size of the sand of 0·65 mm and a filtration surface of 1963 cm^2.

Now, Eqn (9) with the suitable coefficients and exponents (Table 5) must be applied for the screen and sand filters, respectively. By introducing the data, and then isolating it, the volume V can be obtained for the130 μm screen filter:

$$0{\cdot}025 = 1{\cdot}10 \times 10^{-6}\left(2{\cdot}21 \times 10^{9} V\right)^{-0{\cdot}17}\left(1{\cdot}61 \times 10^{5}\right)^{0{\cdot}74} \times (0{\cdot}169)^{0{\cdot}72}(0{\cdot}012)^{-0{\cdot}19}(18145)^{0{\cdot}61} \quad (11)$$

giving a filtered volume V of 68·0 m^3 and the time between washings of 35·2 h. Similarly, for the 0·65 mm sand filter, the result is a volume V of 32·7 m^3 and 16·4 h is the time between two filter cleanings.

Results show that the filter that allows a lower volume to pass before a 49 kPa head loss is reached is the sand filter. This result agrees with other studies (Capra & Scicolone, 2004; Dehghanisanij *et al.*, 2004), despite the finding of Ravina *et al.* (1997) that sand filters usually need a lower backwashing frequency than disc and screen filters when using effluents, except in periods of intense bacterial activity. Although sand filters have the highest number of backwashings, which make the management difficult, they guarantee the best emitter performance (Capra & Scicolone, 2004).

4. Conclusions

Equations have been developed by means of dimensional analysis to relate dimensionless groups that have an influence on the filtration of effluents in microirrigation systems, regardless of the filter being used. Dimensionless groups incorporate variables such as head loss across the filter, filtration level, filtration surface, filtration flow rate, filtered volume, total suspended solids of the effluent, mean diameter of the effluent particles and water density and viscosity.

Experiments with disc, screen and sand filters with different filtration levels were carried out using five different effluents. Data obtained from filtration tests allowed computing the different dimensionless groups, which were statistically adjusted with the developed equations. Despite adjustments of the theoretical equations with experimental data being significant, regression coefficients are not always high. In terms of the goodness of fit adjustments between equations and experimental data, both effluent and filter are influential.

The best regression was achieved with a potential equation that incorporates the six dimensional groups obtained through Buckingham's method. The different coefficients and exponents of this general equation were obtained for each type of filter evaluated: screen, disc and sand.

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