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Research Paper

Effects of the underdrain design on the pressure drop in sand filters

Toni Pujol [a], Gerard Arbat [b,*], Josep Bové [b], Jaume Puig-Bargués [b], Miquel Duran-Ros [b], Joaquim Velayos [a], Francisco Ramírez de Cartagena [b]

[a] Department of Mechanical Engineering and Industrial Construction, University of Girona, C. de Maria Aurèlia Capmany, 61, 17071 Girona, Spain

[b] Department of Chemical and Agricultural Engineering and Technology, University of Girona, C. de Maria Aurèlia Capmany, 61, 17071 Girona, Spain

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The effect of the nozzle geometry on the pressure drop of a sand filter was experimentally studied. Four nozzles were analysed: one commercially produced with a conical shape and three alternative cylindrical underdrains that differed in the location and the number of slots. Experiments in both filtration mode and backwashing conditions for a wide range of superficial velocities were carried out. The results reported a reduction of the filter energy consumption greater than 20% could be achieved by simply modifying the position of the slots above the surface of the underdrain element. The effects of the nozzle were further investigated by means of an analytical model that correctly predicted the pressure drop of the water flow through the filter. The model confirmed that the distribution of the slots in the underdrain was a critical factor for determining the length of the region with a non-uniform flow within the sand. When using the commercial nozzle at flow rates $>0.85\ l\ s^{-1}$, this region produced the major contribution to energy losses in the filter due to increases in the tortuosity of the water path within the porous medium. From these results, it is suggested that an affordable way to increase the energy efficiency of already existing installations would be to replace the current underdrain elements with new improved designs.

1. Introduction

Microirrigation systems allow for highly efficient water use. They are also the most suitable irrigation systems for applying reclaimed wastewater for irrigation (Capra & Scicolone, 2007). Both reasons explain why microirrigation is extensively used in many countries such as India, China, Spain and USA, with microirrigated areas in each of these countries over 1.5 Mha (ICID, 2011). In the case of Spain, microirrigation covers up to the 49% of the irrigated land (MAGRAMA, 2015) and Israel, the country with the highest percentage of microirrigated surface area, this system accounts 73% of the total irrigated surface area.

* Corresponding author.
E-mail address: gerard.arbat@udg.edu (G. Arbat).
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Nomenclature

CFD	Computational fluid dynamics
D	Diameter in the Darcy–Weisbach equation, m
d	Diameter ($<D$) for calculating the minor loss coefficient K in expansions and contractions, m
D_F	Filter inner diameter, m
D_{F0}	Equivalent filter diameter at the uniform flow region, m
D_{F1}	Equivalent filter diameter at the nozzle, m
D_p	Mean particle diameter, m
f	Friction factor
H	Sand height, m
K	Minor loss coefficient
K_s	Minor loss coefficient for the sand medium
K_x	Term employed in the calculation of K_s
L	Length in the Darcy–Weisbach equation; Length of the sand column, m
L_{nu}	Length of sand with non-uniform flow, m
L_T	Filter total length, m
L_u	Length of sand with uniform flow, m
p_{in}	Pressure at the inlet of the filter, Pa
p_{out}	Pressure at the outlet of the filter, Pa
Q	Volumetric flow rate, $m^3\ s^{-1}$
r	Correlation coefficient
Re	Reynolds number
S	Filtration surface area of the nozzle, m^2
v	Mean flow velocity, $m\ s^{-1}$
v_s	Superficial velocity, $m\ s^{-1}$
x	Ratio D_{F0}/D_{F1}
Δp	Pressure difference between p_{in} and p_{out}, Pa
Δp_{12}	Total pressure drop in the filter ($=\Delta p$; used in the analytical model), Pa
Δp_s	Pressure drop through the sand medium, Pa
Δp_w	Pressure drop through water only regions, Pa
ε	Sand porosity
λ	Tortuosity
μ	Water viscosity, Pa s
ρ	Water density, $kg\ m^{-3}$
ϕ	Sphericity factor

Subscripts (in Δp_s and Δp_w)

m	Minor (or secondary) losses
p	Primary losses

In general, the adoption of more efficient irrigation systems, as microirrigation, has led to an increase in the use of energy (Tarjuelo et al., 2015). The modernisation of the irrigation systems in Spain has reduced the consumption of water per hectare by 21% between 1950 and 2007, but the corresponding energy demand has increased by 657% (Corominas, 2010). In fact, Spain, with values above 774 GWh, is the Mediterranean country with the highest energy demand for irrigation (Daccache, Ciurana, Diaz, & Knox, 2014). To cope with this problem, several studies have been carried out at the irrigation network level in Spain which have suggest solutions to reduce energy consumption in pressurised systems (Carrillo Cobo, Camacho Poyato, Montesinos, Rodríguez Díaz, 2014; Jiménez-Bello, Royuela, Manzano, Prats, & Martínez-Alzamora, 2015; Moreno, Córcoles, Tarjuelo, & Ortega, 2010), and the pumping equipment (Fernández García et al., 2014; Mora, Vera, Rocamora, & Abadia, 2013; Urrestarazu & Burt, 2012), but there is a lack of studies aimed at analysing the filtration system.

In a microirrigation system, the energy needs are mainly due to providing the required pressure in the filters; a pressure which is well above that required for the drip emitters. Although the trend is to operate with emitters at lower pressures, the pressure requirements of filters have not been substantially changed. Burt (2010) already identified that a reduction of the pressure required for filtration could significantly reduce pressure requirements in the microirrigation systems. It is noticeable that pressure drop produced by the auxiliary elements of a porous medium filter is quantitatively more important than that occurring in the porous medium itself (Burt, 2010; Mesquita, Testezlaf, & Ramirez, 2012).

Arbat et al. (2011) used computational fluid dynamics (CFD) techniques to predict pressure losses produced by the different elements of a microirrigation sand filter and pointed out the importance of the underdrain design in the filter's hydraulic behaviour and therefore in the resulting pressure drop produced by the entire filter. Mesquita et al. (2012) studied the pressure drop produced in three different commercial filters, which had the three different underdrain configurations most commonly used by manufacturers: manifold, disc and nozzle types. According to their results, the nozzle underdrain-type filter was the one that produced less pressure drop, independent of the media size and bed depths tested in their experiments. Bové et al. (2015b) presented a new underdrain design that modified the geometry of a commercial nozzle by (1) increasing the cross-sectional area at the outlet of the nozzle and (2) placing some of the slots at the top of the nozzle whereby a more direct exit of the streamlines was favoured and therefore the pressure drop was reduced. Based on the CFD simulations, the new underdrain designed by Bové et al. (2015b) reduced the pressure drop in the complete filter by 35% compared with the similar commercial nozzle.

The objectives of the present paper are: (1) to construct three different new underdrains following the suggestions of previous CFD studies by Bové et al. (2015b) and the analytical study of Arbat et al. (2013) who focused on improving the efficiency of sand media filters; (2) to test under laboratory conditions the three new underdrain designs and to compare the resulting pressure drop with those produced by a commercial nozzle; and (3) to use a modified version of the analytical model of Arbat et al. (2013) in order to predict and explain the effect of the different underdrain configurations, the granular medium, and their interactions.

2. Material and methods

2.1. Experimental setup

The laboratory sand filter was a scaled version of a commercial filter (Arbat et al., 2013). The main dimensions of the laboratory filter were an inner diameter (D_F) of 200 mm and a total length (L_T) of 750 mm (Fig. 1). An inner plate with an