Computational simulation of hydraulic characteristics for laminated sand filter

Xiao Xinmian[1], Dong Wenchu[2], Pan Lin[1], Yu Lifeng[1]
(1. *College of Engineering and Technology, Huazhong Agricultural University, Wuhan* 430070, *China*;
2. *State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan* 430072, *China*)

Abstract: Aiming at the problem of emitter jamming in micro-irrigation engineering, the optimal number of laminated sand filter was discussed with stated filter diameter, through abundant hydraulic characteristics tests and back flushing tests. Equations of hydraulic characteristics in sand filter lamination and formulas of filtrated head-loss are put forward in the study. The results of experiments show that the suggested formulas of filtrated head-loss are more precise than the former empirical formulas: the relative error is 3.18% with specified velocity. This study offers references for research and development of new types of sand filter.

Key words: micro-irrigation; sand filter; lamination; hydraulic characteristics
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0 Introduction

It is essential to filter irrigation water in micro-irrigation engineering to avoid emitter jamming that it would cause the system failure. As the sand filter can both filtrate in 3-dimensions and has strong ability in feculences capture, it is the most extensive and efficient filtration equipment[1]. The sand filter has a long development history which from early single kettle sand filter[2], designed by Australian Jam. Louis[3], to double kettle sand filter with stainless filtration head, which has been used in most micro-irrigation engineering now. The great progress has been made in both manufacture process and filtration effect of sand filters. In 2006, C. Steicke et al, carried on a research on floating medium in a mechanical filtration mode, and also tested and compared the characteristics of sand filter. The research indicated that floating medium filter was better and more applicable to recirculating aquaculture systems than conventional pressurized sand filter, and demonstrated the trend for sand filter amelioration[4]. M.G. Healy et al. had studied the treatment of dairy wastewater using constructed wetlands and intermittent sand filters in the same year, suggested design guidelines for sand filter[5]. In 2007, the British scholar Howard took study of how to improve the sand filter performance[6]. However, with the demand of water surpassing its supply, it is important to study anti-clogging filtration equipment and develop a new sand filter with good hydraulic characteristics in micro-irrigation technical field.

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Biography：Xiao Xinmian(1956－), female, associate professor, majored in Facilities Agriculture, Energy Engineering and Water-saving Irrigation Technology. College of Engineering and Technology, Huazhong Agricultural University, Wuhan 430070, China. Email: xiaoxinmian@mail.hzau.edu.cn

1 Principles of filtration

Filtration is the result of adhesive force between impurity particles and filtration material and its performance depends on the mechanical filtration, precipitation, and contact flocculation to remove feculences in water[7]. In the process of filtration, there is a wake flow in the aperture of filtering layer, and impurity particles moving in the streamline. In mechanical filtration, impurity particles that are larger than aperture will be held up by the surface of the filtering layer when the streamline passes through. Precipitation happens when large particles drop rapidly causing small impurities to break away from the streamline due to gravity; the escaped particles are held up by the huge deposit area in the filtering layer, which in this way acts similarly to a superimposed sedimentation tank. Filtration material in filtering layer can be regarded as contact adsorption medium in contact flocculation[8]. When flow rates sinuously in aperture of filtering layer and the impurity particles in water move to the surface of the filtration material, impurity particles are adsorbed into the surface of filter material particles by Van der Waal gravitation, electrostatic forces, and some especial chemical absorbability, so feculences can be removed[9]. Figure 1 shows the principle of removing feculence by sand.

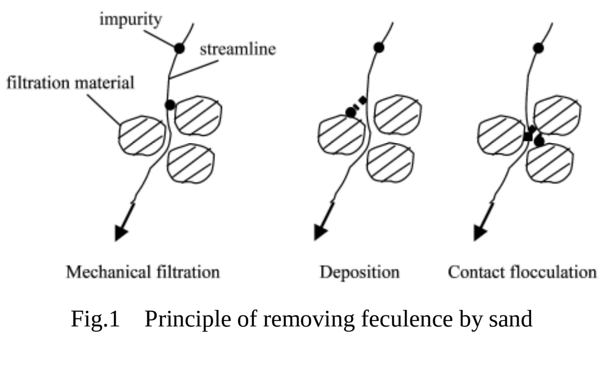

Fig.1 Principle of removing feculence by sand

2 Hydraulic characteristics of laminated sand filter

2.1 Structure and principle of laminated sand filter

Laminated sand filter is a new kind of pressurized filter that collects filtered water by the filter head of lamination in sand filter equipment. Laminated sand filter is mainly composed of intake pipe, kettle body, water distributor, feed inlet, supporting plates, filter head of lamination, hydroecium, and outlet pipe. Its exterior structure is similar to sand filter of aperture that is used mostly in micro-irrigation. The main difference between both filters is the filter head. Reference 10 shows a diagram of the laminated sand filter Irrigation water flowing from intake pipe is distributed equably to kettle body by water distributor, then is collected in the hydroecium by filter head of lamination through the filtering layer, at last be sent to irrigation pipe by the outlet pipe. Filter head of lamination is the key equipment of the filter, which is composed of many plastic ring disks with grooves. When sundries in the water flow through lamination, the sand filter of lamination intercepts and collects them in the outside wall and grooves of the filter. In order to eliminate jam, feculences are flushed in the inside-wall and grooves when pressurized water flow through filter element to lamination[10].

2.2 Hydraulic characteristics of filter head of lamination

Filter head of lamination is the catchment of laminated sand filter, whose hydraulic characteristics are the important factors to evaluate filter. To determine the hydraulic characteristics of laminated sand filter, the authors carried out many experiments with hydraulic characteristics.

Experiment 1 is to confirm the numbers of lamination: diameter of filter head Φ1=20 mm, vertical type filter kettle, numbers of lamination are 12, 24, 36, 48. The curve that describes the relationship between the number of lamination and head-lose is summarized in Reference 10.The test result is that 48 lamination filters have the best hydraulic performance with specified flow rate according to results of hydraulic characteristics tests. Filtrated head-loss with 48 lamination filters is the least, that with 36 lamination filters takes the second place, that with 24 lamination filters is the third, and that with 12 lamination filters is the last, i.e, it has the biggest filtrated head-loss[10].

Experiment 2 is to research the influence of both kettle's type and direction of water on effectiveness of the filter, with diameter of filter head Φ1=20 mm, and the number of lamination is 36 for both vertical and horizontal type filter kettle respectively. The experimental data are presented in Table 1 collected from several sets of experiments. Figure 2 shows the hydraulic characteristics curves of both vertical horizontal type filter by regression analysis. And equations of hydraulic characteristics under different conditions are given in Table 2.

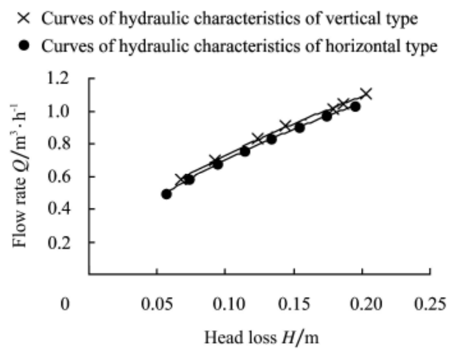

Fig.2 Graph of hydraulic characteristics of different type for 36 laminations

Table 1 Hydraulic characteristics test of different types for 36 laminations

	Measuring Point	1	2	3	4	5	6	7	8
Vertical type	Inlet Pressure H_1/m	1.133	1.088	0.256	0.774	1.007	1.26	1.085	
	Outlet Pressure H_2/m	0.93	0.902	0.077	0.63	0.883	1.168	1.018	
	Head Loss H/m	0.203	0.186	0.179	0.144	0.124	0.092	0.067	
	Flow Rate Q/m$^3\cdot$h^{-1}	1.106	1.046	1.013	0.907	0.831	0.701	0.581	
Horizontal type	Inlet Pressure H_1/m	0.838	0.775	0.703	0.632	0.551	0.461	0.370	0.277
	Outlet Pressure H_2/m	0.645	0.604	0.552	0.500	0.439	0.370	0.298	0.223
	Head Loss H/m	0.193	0.171	0.151	0.132	0.112	0.091	0.072	0.054
	Flow Rate Q/m$^3\cdot$h^{-1}	1.021	0.962	0.895	0.827	0.752	0.671	0.584	0.484

Table 2 Equations of hydraulic characteristics for different conditions

Number of lamination	States	Hydraulic characteristic equation
12	Vertical type	Q=1.87$H^{0.67}$
24	Vertical type	Q=3.29$H^{0.69}$
36	Vertical type	Q=2.73$H^{0.57}$
	Horizontal type	Q=2.67$H^{0.58}$
48	Vertical type	Q=2.87$H^{0.57}$
36	Filtering	Q=2.04$H^{0.76}$
	Back-flushing	Q=1.85$H^{0.73}$
48	Filtering	Q=2.37$H^{0.74}$
	Back-flushing	Q=2.27$H^{0.72}$

2.3 Filter and back-flushing characteristics of laminated sand filter

After a period of time, the filter will be jammed with feculences. Back-flushing could be used to clear up the backlog. It is accomplished by flushing the filtering layer with pressured clean water in reverse direction, which makes filtering layer loose and dilate to remove feculences [9]. To determine filtering and back-flushing performances of sand filter of lamination, sand filtering and back-flushing experiment was carried out with filter head which numbers of lamination are respectively 36 and 48. Diameter of quartz sand is 0.3～1.3 mm; depth of filtering layer is 34 cm. After testing and data processing, the graph that describes the relationship between flow rate and head-loss in sand filtering and back-flushing was summarized in Reference 10. Equations of head-loss are given in Table 2.

2.4 Analysis of test results

1) From Table 1, it can be obtained that hydraulic characteristics of sand filter of lamination have no relation to the type of filter kettle body.

2) By analysis of experiments, the effects of back-flushing of 36 and 48 lamination filters are both good. Their sand filter hydraulic characteristics curves and back-flushing performance curves are very close. However, the back-flushing effect of 48 lamination filters is better than 36, and its back-flushing performance curve almost in accordance with its filter hydraulic characteristics curve[10].

3) The suggested formula (as shown in Fig.2) of head-loss of filter that is educed by hydraulic test and the regression analysis coincides with hydraulic rule [13, 14].

3 Hydraulic computing Formulas of laminated sand filter

3.1 Fundamental hydraulic formula

There are many empirical formulas to calculate the head loss of filter bed[15]. Carmen-Kozeny formula and Leva formula are applicable to calculate filtration head-loss of filter [7]. For easy comparison, we put them in the form like $H=kf(v)$, ziv.

Carmen-Kozeny formula

$$H_{ck}=\frac{36K\mu}{g\rho\psi^2 d_e^2}\cdot\frac{(1-\varepsilon)^2}{\varepsilon^3}Lv \qquad (1)$$

Leva formula

$$H_l=\frac{200\mu}{\rho g\psi^2 d_e^2}\cdot\frac{(1-\varepsilon)^2}{\varepsilon^3}Lv \qquad (2)$$

In the above formulas, H denotes head-loss when depth of filtering layer is L, m; k is dimensionless coefficient, k=5, for water filtering; g is acceleration of gravity; ρ is density of water, kg/m^3; μ is dynamic viscosity of water, Ns/m^2; ψ represents sphericity coefficient of filter material; d_e is equivalent diameter of filter material, mm; ε denotes porosity of filter material; v is velocity of flow, m/s; and L represents depth of filtering layer, m.

3.2 Hydraulic formula of sand filter for micro-irrigation

It was concluded that the values of filtration head-loss calculated by both Carmer-Kozeny and Leva formulas were bigger than experimental values [7]. So it is less accurate to calculate head-loss of sand filter for micro-irrigation by these formulas. Reference 3,derived hydraulic formula of breakstone and sand pressure type filter for micro- irrigation.

$$H_{mi}=\frac{34.74\mu^{0.48}}{\rho^{0.48}g\psi^{1.48}d_e^{1.48}}\cdot\frac{(1-\varepsilon)^{1.48}}{\varepsilon^3}Lv^{1.52} \qquad (3)$$

Formula 3 can be used to calculate head-loss of sand filter of lamination in principle. In order to both seek best hydraulic formula for filter of lamination and analyze propinquity of calculating head-loss and fact, it is essential to experiment with hydraulic characteristics.

3.3 Hydraulic computing formulas of laminated sand filter

Hydraulic tests were carried out by vertical type laminated sand filter with a diameter of kittler body D is 315 mm. Experimental filter material is quartz sand having ψ=0.82, ε=0.42, d_e=0.00059m. $\mu=10^{-3}$Ns/m^2, ρ=1000 kg/m^3, g =9.81m/s^2, L=34 cm. Experimental data collected from several sets of experiments have been denoted in Table 3.

Table 3 Hydraulic characteristics test for sand filter of lamination

Measuring Point	1	2	3	4	5	6	7	8	9
Inlet Pressure p_1/MPa	0.145	0.187	0.229	0.117	0.170	0.203	0.252	0.255	0.307
Outlet Pressure p_2/MPa	0.122	0.166	0.212	0.104	0.157	0.192	0.244	0.248	0.302
Head Loss H/m	2.347	2.143	1.735	1.327	1.224	1.122	0.816	0.714	0.459
Flow Rate Q/m$^3\cdot$h^{-1}	15.901	14.42	12.759	11.866	10.648	9.956	8.664	8.421	6.963
Flow Velocity v×10^{-3}/m·s^{-1}	28.303	25.668	22.711	21.121	18.953	17.72	15.42	14.99	12.39

The formula of head-loss of filter is educed by hydraulic test and the regression analysis:

$$Q=9.847H^{0.491} \text{ or } H=0.01Q^{2.02}$$

Q is flow rate, m^3/h; H is head-lose, m.

To put it in unified form:

$$H_{\rm lam}=3572.3v^{2.02} \qquad (4)$$

After substituting sphericity coefficient of filter material ψ=0.82, ε=0.42, d_e=0.00059 m, $\mu=10^{-3}$Ns/m^2, ρ=1000 kg/m^3, g =9.81 m/s^2, L=34 cm into formula 3, it can be obtained:

$$H_{mi}=\frac{34.74(\mu\times10^{-3})^{0.48}\times0.34}{1000^{0.48}\times9.81\times0.82^{1.48}\times0.00059^{1.48}}\cdot\frac{(1-0.42)^{1.48}}{0.42^3}\cdot v^{1.52}=773v^{1.52}$$

In a similar way, corresponding expressions like $H=kv^{\alpha}$ are given in Table 4.

The head-loss calculated by formula 4 is $H_{\rm lam}$=1.185 m when design velocity v is 0.01895 m/s. To compare with measured value of $H_{\rm meas}$=1.224 m, an error $\triangle H$=−0.039 m can be obtained; the relative error $P_{lam}=\triangle H_{lam}/H_{meas}\times$100%=3.18%. By Formula 3, $H_{\rm lam}$=1.863 m, $\triangle H$=0.639 m, P=52.2%. By Formula 2, $H_{\rm l}$=2.549 m, $\triangle H$=1.325 m, P=108.25%. And by Formula 1, $H_{\rm ck}$=2.293 m, $\triangle H$=1.069 m, P=87.3%. As shown in Table 4, there is head-loss under other velocities. From Table 4, we can see that the head-loss value calculated by Formula 1 or Formula 2 is much bigger than the measured value; likewise, by using the formulas of breakstone and sand pressure type filter for micro-irrigation the calculated value is bigger than measured value. However, the head-loss value calculated with the formula educed by hydraulic test is close to measured value. In nine measuring points, there are five points with error below 4.3% and seven points with error below 10%, so calculating precision can meet the need of operating requirement.

Table 4 Computation of head-loss for filtering

$V_{masuree}/10^{-3}$ m • s^{-1}	28.303	25.668	22.711	21.121	18.953	17.72	15.42	14.99	12.39
$H_{measure}(m)$	2.347	2.143	1.735	1.327	1.224	1.122	0.816	0.714	0.459
$H_{ck} = 121v(m)$	3.424	3.106	2.748	2.556	2.293	2.144	1.866	1.814	1.499
$H_l = 134.5v(m)$	3.807	3.452	3.055	2.841	2.549	2.383	2.074	2.016	1.666
$H_{mi} = 773v^{1.52}(m)$	3.427	2.954	2.453	2.197	1.863	1.682	1.362	1.304	0.976
$H_{lam} = 3572.3v^{2.02}(m)$	2.664	2.187	1.708	1.475	1.185	1.035	0.781	0.738	0.502
$\Delta H_{mi} = H_{mi} - H_{meas}(m)$	1.080	0.811	0.718	0.87	0.639	0.56	0.546	0.59	0.517
$P_{mi} = \Delta H_{mi}/H_{meas} \times 100\%$	46.02	37.84	41.38	65.56	52.2	49.91	66.91	82.63	112.6
$\Delta H_{lam} = H_{lam} - H_{meas}(m)$	0.317	0.044	−0.027	0.148	−0.039	−0.087	−0.035	0.024	0.043
$P_{lam} = \Delta H_{lam}/H_{meas} \times 100\%$	13.51	2.050	1.560	11.15	3.18	7.750	4.290	3.360	9.370

4 Conclusions

1) Filter head of lamination is the catchments element of sand filter. The optimal number of lamination is 48 by hydraulic test and regression analysis when diameter of filter head is 20mm.

2) Hydraulic characteristics of sand filter of lamination had no relation to type of filter kettle body. Both vertical and horizontal types have the same hydraulic characteristics.

3) Back-flushing effects of 36 and 48 lamination filter are both good. Their sand filter hydraulic characteristics curve and back-flushing performance curve are very close. However, back-flushing effect of 48 lamination filter is better than 36, and its back-flushing performance curve almost accords with its filter hydraulic characteristics curve.

4) The suggested formula of head-loss of filter, H=0.01$Q^{2.02}$, is educed by hydraulic test and the regression analysis, coincides with the form of filter hydraulic formula, H=kQ^{α}. It offers references for calculating head-loss of sand filter, with confirmed k and α by experiment.

5) The experiments show that the suggested formulas of head-loss[5] of filter in this paper are more precise than the former empirical formulas and others. With specified velocity, the formulas can meet the operating requirement with an error of 3.18%.

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叠片式砂过滤器水力特性模拟计算

肖新棉[1]，董文楚[2]，潘 林[1]，余利锋[1]

（1．华中农业大学工程技术学院，武汉 430070； 2．武汉大学水资源与水电工程科学国家重点实验室，武汉 430072）

摘 要：针对微灌工程中灌水器堵塞的问题，通过大量的水力性能测试和反冲洗性能试验，探讨了叠片式砂过滤器当滤管直径一定时的最佳叠片数，提出叠片式砂过滤器的水力性能特性方程和过滤水头损失公式，试验证实所建立的叠片式砂过滤器的水头损失公式比原有经验公式的计算精度高，即在设计流速条件下误差仅为 3.18%，为开发研究新型砂过滤器提供参考。

关键词：微灌；砂过滤器；叠片；水力特性