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Research on head loss of pre-pump micro-pressure filter under clean water conditions

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ABSTRACT

Filters are important pieces of equipment to ensure the normal operation of micro-irrigation systems, and the head loss is a key indicator to evaluate their hydraulic performances. To reduce the head loss and energy consumption, a new type of filter for treating surface water – the pre-pump micro-pressure filter was proposed. The pre-pump micro-pressure filter was studied, and physical model tests on the flow rate, water separator type, and filter screen area were conducted under clean water conditions. Statistical and dimensional analysis methods were used to analyze the test results. Our results showed that the order of the factors affecting the head loss of the filter was flow rate > water separator type > filter screen area. The various water separator types showed no significant differences in terms of head loss, while the different flow rates showed significant differences. A head loss prediction model was constructed, and the coefficient of determination R^2 reached 0.987. Our results can provide technical support for new filter development and enrich the theory of micro-pressure filtration.

Key words: dimensional analysis, filter, head loss, micro-irrigation system, multiple linear regression

HIGHLIGHTS

- The predicted head loss of pre-pump micro-pressure filter has a high regression coefficient. The average relative error of the predicted value is 6.07%, which shows that the calculation equation is an ideal head loss prediction model.
- The order of the factors affecting the head loss of the filter is as follows: flow rate > water separator type > filter screen area.

INTRODUCTION

During the operation of micro-irrigation systems, the flow channel of the irrigator is easily blocked by impurities, which significantly affects the irrigation efficiency. As the core hub of the entire micro-irrigation system, the filter plays a key role in purifying water sources and filtering impurities. At present, the commonly used filters on the market mainly include mesh filters, sand filters, disc filters, hydrocyclone filters, and combined filters. These filters operate by post-pump forced-pressure filtration and flushing; specifically, the filtration or flushing is completed under strong pressure after water enters the pump.

At present, experts and scholars have performed a considerable amount of research on the hydraulic and filtration performances of sand filters, disc filters, mesh filters, and other filtration equipment. The sand filter (Elbana *et al.* 2013; Marcio *et al.* 2019; Carles *et al.* 2019a, 2019b; Fábio *et al.* 2020; De *et al.* 2021) has a good filtering ability for solid suspended particles of various sizes in water, but it is easy to destroy the structure of the sand layer in the sand tank during washing. The disc filter (Yurdem *et al.* 2008; Demir *et al.* 2009; CUI *et al.* 2019) has a good filtering effect, but the head loss is large, and it is generally used as the final filter. The mesh filter is the most widely used in drip irrigation systems due to its simple manufacturing process, good filtering performance, convenient manufacturing, and easy installation. Therefore, many scholars have conducted detailed research and exploration on mesh filters and modified current mesh filters. However, at present, the methods of dimensional analysis and experimental exploration are mainly used to study various forms of mesh filters under different flow rates and sand contents and to determine the empirical equations for the head losses of various forms of filters (Capra & Scicolone 2004; Siriwardene *et al.* 2007).

Duran-Ros *et al.* (2010) established an equation for calculating the head loss of sand–gravel, mesh, and disc filters:

$$\frac{v_f \cdot C^{1/2}}{\Delta H^{1/2}} = c \cdot \left(\frac{\rho}{C}\right)^{e_{10}} \cdot \left(\frac{\mu}{\Delta H^{1/2} \cdot C^{1/2} \cdot D_p}\right)^{e_{11}},$$

where v_f is the water flow velocity m/s, C is the total suspended solids (TSS) concentration of the influent kg/m^3, ΔH is the total head loss of the filter Pa, c is the empirical coefficient dimensionless, and ρ is the water density kg/m^3, μ is the viscosity of water Pa s, D_p is the diameter of the inlet and outlet pipe m, e^{10}, e^{11} are empirical indexes. Puig-Bargues *et al.* (2005) used dimensional analysis to obtain an equation for calculating the filter head loss under turbid water conditions:

$$\frac{\mu}{\Delta H^{1/4} \cdot Q^{1/2} \cdot C^{3/4}} = \mathrm{a} \cdot \left(\frac{\Delta H^{3/4} \cdot V}{C^{3/4} \cdot Q^{3/2}}\right)^{e_1} \cdot \left(\frac{\Delta H^{1/2} \cdot A}{C^{1/2} \cdot Q}\right)^{e_2} \cdot \left(\frac{\Delta H^{1/4} \cdot \emptyset f}{C^{1/4} \cdot Q^{1/2}}\right)^{e_3} \cdot \left(\frac{\Delta H^{1/4} \cdot P_d}{C^{1/4} \cdot Q^{1/2}}\right)^{e_4} \cdot \left(\frac{\rho}{C}\right)^{e_s}$$

where μ is the water viscosity in Pa s, ΔH is the total head loss across the filter in Pa, Q is the flow rate across the filter in m^3/s, C is the concentration of TSS in the filter influent in kg·m^3, V is the water volume across the filter in m^3, A is the total filtration surface in m^2, F_f is the filtration level or filter pore in m, ρ is the water density in kg·m^3, a is an empirical coefficient and e$_1$, e$_2$, e$_3$, e$_4$ and e$_5$ are empirical exponents that take different values for each filter type. Duran-Ros *et al.* (2010) and Puig-Bargues *et al.* (2005) based on the dimensional analysis method, established by their predecessors to calculate the head loss of various filters, comprehensively considered the various variables that affect the head loss of the filter, namely filtration accuracy φ_f, average solid particle size D_p, filtration surface area A, filtration volume Q, suspended particle content C, overflow V, viscosity coefficient μ and density ρ, and established correction equations for calculating head loss of various filters $f = (\Delta H, \phi_f, D_p, A, Q, C, v, \mu, \rho) = 0$. The test results showed that the head loss value calculated by the dimensional analysis method derived and improved by Buckingham's theorem was in good agreement with the test data, and the correlation was high. This research result has laid a solid mathematical model foundation for the correct calculation of the head loss of the sand–gravel filter for micro-irrigation. Pinto *et al.* (Marinaldo *et al.* 2016) obtained the relationship between the head loss and the flow when researching and developing a new type of mesh filter system. Zong *et al.* (Zong *et al.* 2015) conducted tests on mesh filters for tap-water and sand–water mixture conditions and established a calculation equation for the head loss of self-cleaning mesh filters using dimensional analysis:

$$\frac{\Delta H}{\rho v_f^2} = \mathrm{b}\left(\frac{\emptyset_f}{D_p}\right)^{k_8}\left(\frac{A}{D_p^2}\right)^{k_9}\left(\frac{Q}{v_f D_p^2}\right)^{k_{10}}\left(\frac{\rho v_f D_p}{\mu}\right)^{k_{11}},$$

where ΔH is the total head loss of the filter Pa, ρ is the water density kg/m^3, v_f is the water flow velocity m/s, b is the empirical coefficient, φ_f is the filter level or filter gap m, and D_p is the inlet and outlet pipe inner diameter m, A is the total filtration area m^2, Q is the flow rate through the filter m^3/s, μ is the water viscosity Pa s, and k is the empirical index. The 11 influencing factors of the head loss were taken as the parameters of the filtration performance. The results showed that the predicted and measured head losses had a high correlation coefficient. Wu *et al.* (2014) conducted hydraulic performance tests on 15 types of mesh filters and established a head loss model using dimensional analysis. This mathematical model not only considers the influence of the mesh filter structure size on the head loss, but also focuses on the analysis and introduction of the influence factors of the filter medium. The correlation coefficient (R^2) between the measured and predicted values was 0.97. Thus, the model had high accuracy. This research result has important reference value in the structural design optimization and hydraulic performance analysis of the mesh filter. Liu *et al.* (2015) performed tests on the head loss of Y-type screen filters with/without clogging and obtained the relationship between the sediment particle size and screen filter. Furthermore, they examined the relationship between the head loss, flow rate, and degree of blockage. Liu *et al.* (2019) conducted experimental research on vertical and horizontal self-cleaning mesh filters and established a mathematical expression relating the flow rate and head loss by investigating the relationship between the inlet water flow rate, sand content, filtration time, and filter head loss. $H = \varepsilon Q^2/2A^2 g + \Delta H$, where A is the cross-sectional area of the filter m^2; Q is the water flow rate m^3/h; H is the total head loss m; ΔH is the height difference between the inlet and outlet m; and ε is the head loss coefficient. Shi *et al.* (Shi *et al.* 2020) carried out an experimental study on the relationship between the head loss, flow rate, and sediment content of a new flap net filter, and they established a mathematical model relating the head loss and flow rate. They fitted and verified the mathematical model with the test results. Liu *et al.* (Liu *et al.* 2021) conducted a comprehensive study on the hydraulic performances, filtration performances, discharge performances, and discharge times of mesh filters, established mathematical expressions for the head loss and discharge time, and verified the expressions using the test results: $t_p = \lambda Q/Q_pS/S_pPP_m\mathrm{t}$, where Q is the influent flow rate m^3/h; S is the influent sediment content kg/m^3; P is the percentage of the total mass of sediment particles whose diameter is larger than the mesh of the filter; t is the filtration time when the preset pressure drop is reached s; Q_p is the flow rate m^3/h; S_p is the average sediment content of the discharge kg/m^3; and t_p is the sewage time s. The proposed head loss and sewage time equations can be used to evaluate self-starting screen filters under various working conditions.

At present, most of the filters for micro-irrigation on the market achieve filtration via a post-pump forced pressure, which has issues such as large head losses, high-energy consumption, a large initial investment, and an unstable filtration effect. Because of the issues of the existing filters, a new type of filter, the pre-pump micro-pressure filter, is proposed. 'Pre-pump' refers to the filter being located before the pressurized water pump, and 'micro-pressure' refers to the filter using the water head at the tail of the sedimentation tank to filter and wash under natural conditions. Head loss is an important indicator of the filter's hydraulic performance and operating cost. At present, the established empirical models for the head loss of pre-pump micro-pressure filter have all given satisfactory results, but no experts have proposed a head loss model for pre-pump micro-pressure. The operating conditions of the two are different, so it is necessary to establish the head loss prediction equation of pre-pump micro-pressure under clean water conditions. This paper takes the pre-pump micro-pressure as the research object, carries out the physical model test under clean water conditions, uses the variance analysis method to obtain the order of the factors affecting the head loss of the filter, and establishes the head of the pre-pump micro-pressure under clean water conditions through the dimensional analysis method. The loss prediction model provides a basis for the hydraulic performance and structural optimization of the filter.

MATERIALS AND METHODS

Test equipment and instruments

The circulation system of the pre-pump micro-pressure filter was composed of a mixing tank, a reservoir, a pre-pump micro-pressure filter, and connecting pipes. The pre-pump micro-pressure filter consisted of a filter tank, a water separator, and a stainless-steel filter screen, as shown in Figure 1. Both the reservoir and the filter tank were made from a transparent acrylic board with a thickness of 7 mm, which was convenient for observing the test phenomena. The internal dimensions of the reservoir were a length of 500 mm, width of 300 mm, and height of 600 mm. The filter tank was 300 mm wide and 430 mm high, the length could be adjusted to 505, 705, and 915 mm, and the corresponding filter screen areas were 1,105, 1,582, and 2,060 cm^2, respectively. The water separator type is shown in Figure 2. The differences between the Type 1, Type 2, and Type 3 water separators were the shapes of their heads and tails. The diameters of the inlet pipe and the return pipe were 50 mm, and the diameters of the connecting pipe and the outlet pipe were 75 mm. The flow rate in the test was controlled by adjusting the openings of the inlet and return valves, and the flow rate was measured by a handheld ultrasonic flow meter.

The main instruments and equipment used in this test included a water pump, handheld ultrasonic flow meter, infrared thermometer, digital camera, and stopwatch. The related models (specifications) and functions are shown in Table 1.

Working principle of pre-pump micro-pressure filter

The working principle of the pre-pump micro-pressure filter used in this study is as follows. The sediment particles in the surface water first settle through the sedimentation tank and then flow into the filter from the outlet pipe at the end of sedimentation tank. The water flow is filtered from the inside out, and the clean water flows out of the mesh after filtration. As the filtering progresses, impurities gradually accumulate in the filter screen. When the filter screen is blocked to a certain extent, a discharge operation must be carried out to restore the filtering capacity and filtration efficiency of the filter screen. At this time, the discharge valve is opened to realize hydraulic sand discharge under the action of the natural head of the sedimentation tank. Manual flushing can also be used to remove the water separator, manually flush the filter screen, and reinstall the water separator after flushing.

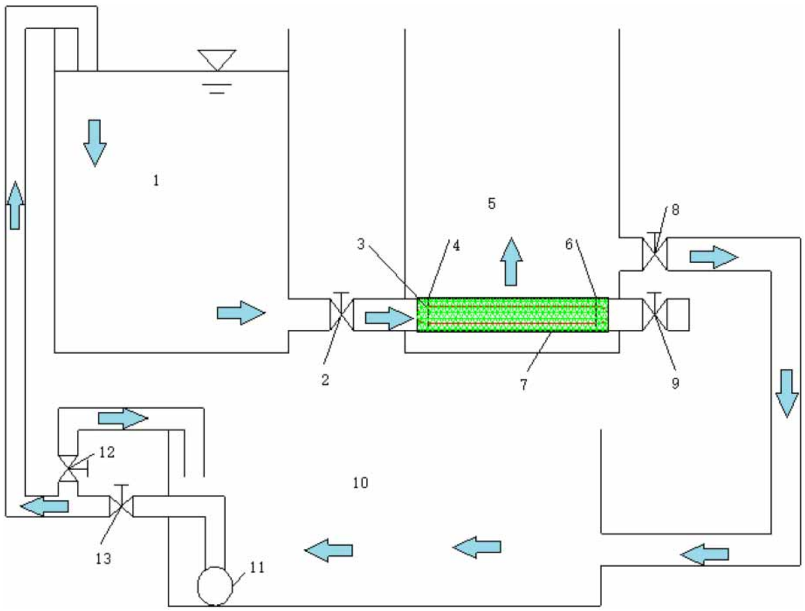

Figure 1 | Schematic diagram of the circulation system of the pre-pump micro-pressure filter. (1) reservoir; (2) water inlet valve; (3) water separator; (4) water inlet; (5) filter tank; (6) water outlet; (7) filter screen; (8) outlet valve; (9) discharge valve; (10) mixing tank; (11) water pump; (12) return water valve; (13) water inlet valve.

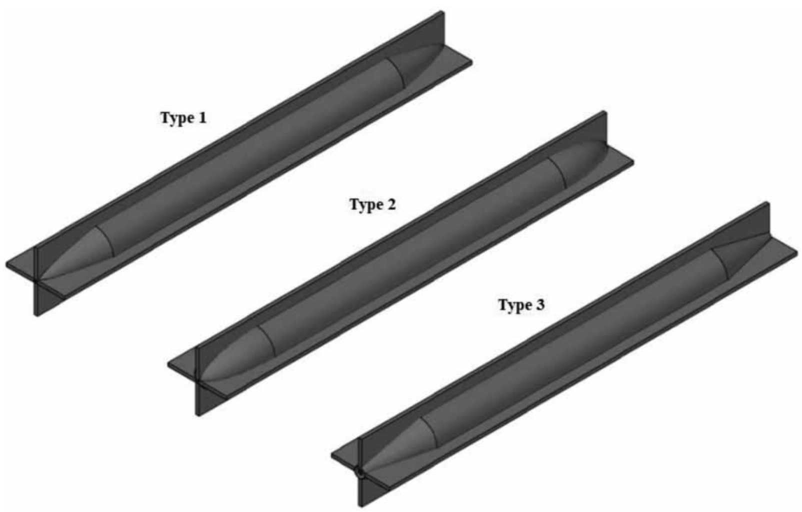

Figure 2 | Three-dimensional diagram of water separators.

Table 1 | Test equipment

Name	Model/Specification	Quantity	Use
Water pump	WQD12-20-1.5	1	Input test water source into system
Handheld ultrasonic flow meter	MSDS-3000H	1	Measured flow rate during test
Infrared thermometer	DE6830B	1	Measured water temperature during test
Stopwatch	–	1	Recorded time
Digital camera	Canon EOS 77D	1	Photographed test phenomenon

Test procedure

The water for the clean water test was tap water, which did not contain dirt and impurities that could block the filter screen. Single-factor physical model tests in which the flow rate, filter screen area, and water separator type were individually varied were carried out. During the test, the flow rate was controlled by adjusting the opening of water inlet valve. The flow rate range of the test device was determined to be 2–9 m^3/h through preliminary tests, and the test flow rates were taken as 2, 4, 6, 7 and 8 m^3/h. The flow rate was adjusted from small to large in order, and an ultrasonic flow meter was used to measure the inlet water flow. The scale set in the reservoir and filter tank was used to read the water level under the corresponding flow rate conditions, and the water level difference between the reservoir and the filter tank was calculated. The flow velocity in the reservoir and filter tank was calculated according to the size of the inlet water flow and then head loss under different test conditions was calculated after calculating the energy in the inlet and outlet sections. The arrangement of the test groups under clean water conditions is shown in Table 2.

RESULTS AND DISCUSSION

Head loss result of pre-pump micro-pressure filter

Full tests were carried out at different flow rates, filter screen areas, and water separators with a total of 45 groups, and the test results are shown in Table 3.

Analysis of variance of test results

Analysis of variance was used to analyze multiple processed test indicators as a whole. This analysis divides the total variation into the variation caused by experimental factors and random variations and compares the relative sizes of the two to determine whether there was a significant difference between the overall means. If there was a significant difference, then this factor had a significant effect (Dai & Yuan 2016). The analysis of variance is based on the assumption that the model is linear, the variance is homogeneous, and the error is random and independent and obeys a normal distribution with a mean of zero. After testing the homogeneity of the variance and the normality and satisfying the basic assumptions, the results for the clean water test were analyzed by analysis of variance. The final analysis results are shown in Table 4. Both the flow rate and water separator type had a significant effect on the clean water head loss ($p < 0.05$). The flow rate had the greatest effect on the clean water head loss, followed by the water separator type, and finally, the filter screen area.

Comparative analysis of multiple factors of head loss

From the analysis of variance results for the clean water test, the inlet water flow rate and water separator type had a significant effect on the clean water head loss, and the filter screen area had no significant effect. The significant factors from the analysis of variance were used for multiple comparison tests. The analysis results are shown in Table 5.

For the clean water head loss, the differences between different levels of the inlet water flow rate A were significant. The greater was the inlet water flow rate, the greater was the clean water head loss. The water separator type had a significant effect on the clean water head loss, but the differences between the different water separator types were not significant. Therefore, the water separator type was not included in the establishment of the clean water head loss prediction model to simplify the modeling process.

Establishment of head loss prediction model

As this experiment involved a relatively complex physical process, it was difficult to guarantee the accuracy of a model derived mathematically. Therefore, dimensional theory was used for analysis (Li 2000). The π theorem requires the m basic physical quantities that affect the system parameters to be independent of each other. Several variables that had an effect on the filter head loss (h_w) were investigated: the aperture of the filter (d_f), the inlet water flow (Q), the area of the filter screen (A), the acceleration of gravity (g), the diameter of the connecting pipe (D), the length of the filter tank (L_1),

Table 2 | Clean water test groups

Test water source	Flow rate (m^3/h)	Water separator type	Filter screen area (cm^2)	Test object
Tap water	2, 4, 6, 7, 8	Not used, Type 1, Type 2, Type 3	1,105, 1,582, 2,060	Pre-pump micro-pressure filter

Table 3 | Head loss of the pre-pump micro-pressure filter under clean water conditions

Flow rate (m^3/h)	Reservoir water level (m)	Filter tank water level (m)	Filter screen area (cm^2)	Water separator type	Head loss (m)
2	0.251	0.236	1,105	Not used	0.0235
4	0.308	0.261	1,105	Not used	0.0717
6	0.383	0.299	1,105	Not used	0.1215
7	0.432	0.323	1,105	Not used	0.1393
8	0.482	0.349	1,105	Not used	0.1761
2	0.280	0.238	1,582	Not used	0.0302
4	0.324	0.258	1,582	Not used	0.0663
6	0.387	0.293	1,582	Not used	0.1053
7	0.433	0.319	1,582	Not used	0.1366
8	0.496	0.352	1,582	Not used	0.1767
2	0.267	0.232	2,060	Not used	0.0316
4	0.293	0.238	2,060	Not used	0.0553
6	0.340	0.242	2,060	Not used	0.1346
7	0.358	0.244	2,060	Not used	0.1537
8	0.391	0.248	2,060	Not used	0.1923
2	0.254	0.233	1,105	Type 2	0.021
4	0.337	0.263	1,105	Type 2	0.074
6	0.427	0.299	1,105	Type 2	0.127
7	0.497	0.327	1,105	Type 2	0.170
8	0.547	0.345	1,105	Type 2	0.201
2	0.276	0.239	1,582	Type 2	0.038
4	0.339	0.260	1,582	Type 2	0.079
6	0.433	0.294	1,582	Type 2	0.139
7	0.495	0.316	1,582	Type 2	0.179
8	0.585	0.351	1,582	Type 2	0.234
2	0.260	0.232	2,060	Type 2	0.028
4	0.307	0.238	2,060	Type 2	0.069
6	0.367	0.242	2,060	Type 2	0.125
7	0.409	0.245	2,060	Type 2	0.164
8	0.461	0.247	2,060	Type 2	0.214
2	0.261	0.234	1,105	Type 1	0.027
4	0.322	0.255	1,105	Type 1	0.067
6	0.433	0.296	1,105	Type 1	0.137
7	0.508	0.326	1,105	Type 1	0.182
8	0.554	0.345	1,105	Type 1	0.209
2	0.264	0.239	1,582	Type 1	0.025
4	0.319	0.240	1,582	Type 1	0.079
6	0.419	0.292	1,582	Type 1	0.127
7	0.502	0.323	1,582	Type 1	0.179
8	0.583	0.353	1,582	Type 1	0.230
2	0.261	0.233	2,060	Type 1	0.027
4	0.301	0.239	2,060	Type 1	0.062

(*Continued.*)

Table 3 | Continued

Flow rate (m^3/h)	Reservoir water level (m)	Filter tank water level (m)	Filter screen area (cm^2)	Water separator type	Head loss (m)
6	0.380	0.243	2,060	Type 1	0.137
7	0.420	0.245	2,060	Type 1	0.174
8	0.458	0.248	2,060	Type 1	0.210
2	0.250	0.231	1,105	Type 3	0.020
4	0.327	0.258	1,105	Type 3	0.070
6	0.436	0.298	1,105	Type 3	0.138
7	0.516	0.331	1,105	Type 3	0.185
8	0.556	0.344	1,105	Type 3	0.212
2	0.265	0.234	1,582	Type 3	0.031
4	0.321	0.240	1,582	Type 3	0.080
6	0.377	0.243	1,582	Type 3	0.134
7	0.435	0.245	1,582	Type 3	0.190
8	0.492	0.248	1,582	Type 3	0.244
2	0.265	0.233	2,060	Type 3	0.032
4	0.315	0.239	2,060	Type 3	0.076
6	0.377	0.243	2,060	Type 3	0.133
7	0.416	0.246	2,060	Type 3	0.170
8	0.473	0.248	2,060	Type 3	0.225

Table 4 | Analysis of variance table results for clean water head loss

Source of variation	Sum of squares	Degrees of freedom	Mean square	F	*p*
Flow rate	0.258	4	0.065	567.438	5.547E-41***
Filter screen area	4.427E-04	2	2.214E-04	1.944	1.538E-01
Water separator type	0.004	3	0.001	11.962	5.080E-06***
Error	0.006	50	1.139E-04		
Total	0.269	59			

Note: ***$p < 0.001$

Table 5 | Multiple comparative analysis of influencing factors of head loss

	Head loss		
Factor	Level	Mean	Significance level $a = 0.05$
Inlet water flow Q	1	0.0278	a
	2	0.0708	b
	3	0.1299	c
	4	0.1687	d
	5	0.2104	e
Water separator type C	1	0.1076	a
	2	0.1243	a
	3	0.1248	a
	4	0.1294	–
Filter screen area A	1	0.1186	–
	2	0.1208	–
	3	0.1251	–

the flow rate of the connecting pipe (v), the average flow rate through the mesh (v_f), and the density (ρ) and viscosity (μ) of water. The relevant parameters are shown in Table 6.

Considering these parameters that affect the head loss of the filter, the following relationship can be established:

$$f(h_w, d, Q, \rho, \mu, A, g, D, L_1, v, v_f) = 0 \tag{1}$$

All the variables (m = 11) and their quality dimension M, length dimension L, and time dimension T were considered, and the dimension matrix obtained is shown in Table 7.

Based on dimensional analysis theory, for the 11 physical quantities analyzed, ρ, d_f, and g were selected as the basic physical quantities to represent the dimensionless quantities. Eight dimensionless quantities were obtained to express the head loss of the filter:

$$\pi_1 = \frac{h_w}{d_f} \tag{2}$$

$$\pi_2 = \frac{Q}{d_f^2 v} \tag{3}$$

$$\pi_3 = \frac{v_f}{v} \tag{4}$$

$$\pi_4 = \frac{\mu}{\rho v d_f} \tag{5}$$

$$\pi_5 = \frac{L_1}{d_f} \tag{6}$$

$$\pi_6 = \frac{g d_f}{v^2} \tag{7}$$

$$\pi_7 = \frac{A}{d_f^2} \tag{8}$$

$$\pi_8 = \frac{D}{d_f} \tag{9}$$

Table 6 | Parameters affecting filter head loss

Variable type	Name	Symbol	Unit	Dimension
Dependent variable	Head loss	h_w	m	[L]
Independent variable	Filter aperture	d_f	m	[L]
	Inlet water flow	Q	m^3/s	$[L^3 T^{-1}]$
	Filter screen area	A	m^2	$[L^2]$
	Acceleration of gravity	g	m/s^2	$[LT^{-2}]$
	Diameter of connecting pipe	D	m	[L]
	Length of filter tank	L_1	m	[L]
	Density of water	ρ	kg/m^3	$[ML^{-3}]$
	Viscosity of water	μ	Pa · s	$[ML^{-1} T^{-1}]$
	Flow rate of connecting pipe	v	m/s	$[LT^{-1}]$
	Average flow velocity through the mesh	v_f	m/s	$[LT^{-1}]$

Table 7 | Dimensional matrix

	h_w	d	Q	A	g	D	L_1	ρ	μ	v	v_f
M	0	0	0	0	0	0	0	1	1	0	0
L	1	1	3	2	1	1	1	−3	−1	1	1
T	0	0	−1	0	−2	0	0	0	−1	−1	−1

Substituting the obtained dimensionless quantities into Equation (1), the following relationship can be obtained:

$$\frac{h_w}{d_f} = \varepsilon\left(\frac{Q}{d_f^2 v}\right)^{k_1}\left(\frac{v_f}{v}\right)^{k_2}\left(\frac{\mu}{\rho v d_f}\right)^{k_3}\left(\frac{L_1}{d_f}\right)^{k_4}\left(\frac{g d_f}{v^2}\right)^{k_5}\left(\frac{A}{d_f^2}\right)^{k_6}\left(\frac{D}{d_f}\right)^{k_7} \tag{10}$$

where ε is an empirical coefficient, and k_1, k_2, k_3, k_4, k_5, k_6, and k_7 are empirical indices.

The dimensionless data from the pre-pump micro-pressure filter were calculated and recorded in an electronic table. After a logarithmic transformation of these dimensionless groups, the SPSS 25.0 statistical software was used for analysis, and a stepwise regression method was adopted. Before performing multiple regression analysis, the data were first tested to see if the assumptions of the multiple regression analysis were met. If the assumptions were met, the multiple regression analysis could be performed. The head loss data under clean water conditions was processed, and a regression standardized residual diagram was drawn. The abscissa is the measured cumulative probability, and the ordinate is the expected cumulative probability. As shown in Figure 3, the data were distributed along the diagonal directions. The regression model satisfied the normality assumption and could be used for subsequent regression analysis.

The results of the empirical coefficient, exponent, and regression coefficient of the regression equation are shown in Table 8. The coefficient of determination R^2 of Equation (10) was greater than 0.9, indicating that the measured data were highly correlated with the simulated data. For a filter with a specific structure, the π term derived from certain geometric variables was constant, which resulted in the exponent of some terms in the equation being zero. In the process of multiple linear regression analysis, the statistical significance level was set to $p < 0.05$. Parameters without statistical significance were not included in the model.

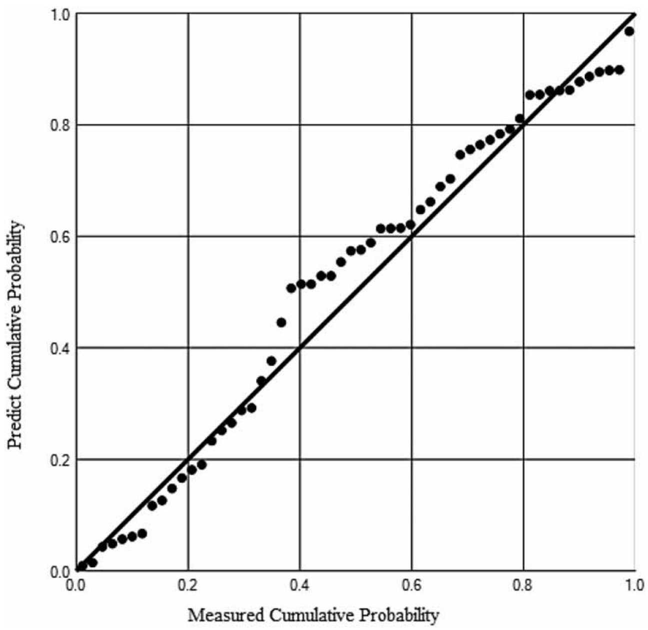

Figure 3 | Normal P–P plot of standardized residuals under clean water conditions.

Table 8 | Regression analysis results of clean water head loss of the pre-pump micro-pressure filter

Equation	Coefficient and exponent			p	Coefficient of determination	Root mean square error
(10)	Coefficient	ε	15.897	1.087E-45***	0.987	0.0868
	Exponent	k_1	0			
		k_2	0			
		k_3	0			
		k_4	0			
		k_5	−0.763	8.510E-53***		
		k_6	0			
		k_7	0			

Note: ***$p < 0.001$.

Substituting the coefficients and exponent values obtained through multiple regression analysis into Equation (10), the following head loss prediction equation of the filter under clean water conditions was obtained:

$$\frac{h_w}{d_f} = 15.879\left(\frac{gd_f}{v^2}\right)^{-0.763} \tag{11}$$

This can be simplified as follows:

$$h_w = 15.879g^{-0.763}d_f^{0.237}v^{1.526} \tag{12}$$

Comparison of measured and predicted values of head loss

The clean water head loss predicted by Equation (10) was compared with the measured head loss, as shown in Figure 4. There was good agreement between the results predicted using the model and the measured results. In some cases, the predicted value was too high or too low. This was expected because there was a certain degree of error in the prediction results of the model. The predicted head loss was very close to the measured head loss, indicating that the model could accurately predict the filter head loss under clean water conditions.

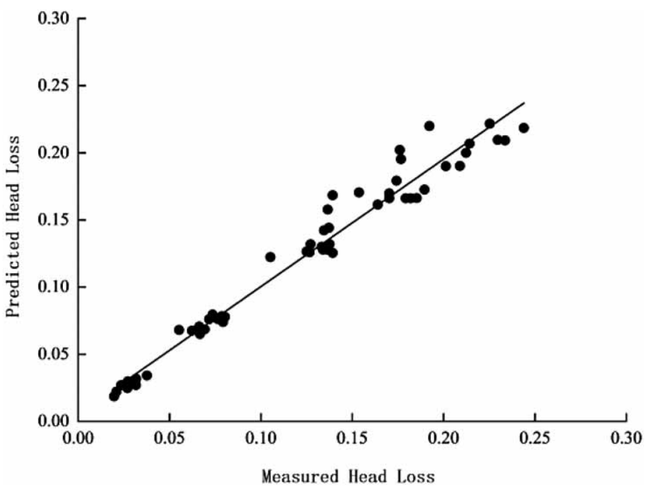

Figure 4 | Comparison of measured and predicted head loss under clean water conditions.

Table 9 | Verification of model prediction accuracy

Working condition	Measured value (m)	Gravitational acceleration, g (m/s^2)	Filter aperture, d_f (m)	Connecting pipe flow rate, v (m/s)	Predicted value (m)	Relative error (%)
1	0.1215	9.8	0.00015	0.5347	0.1330	9.47
2	0.1793	9.8	0.00015	0.5931	0.1558	13.11
3	0.2100	9.8	0.00015	0.7186	0.2088	0.56
4	0.0697	9.8	0.00015	0.3527	0.0705	1.14

Model verification

The reserved test samples were substituted into Equation (10) to verify the accuracy of the model's prediction results. Table 9 shows the comparison between the predicted results of the model and the measured values. The maximum relative error between the predicted value of the model and the measured value was 13.11%, the minimum relative error of the prediction was 0.56%, the average relative error of the predicted value was 6.07%, and the standard error was 2.48%, indicating that the model could predict the head loss of clean water. The main difference between the pre-pump micro-pressure filter and other filters was that the water was filtered by its own potential energy. The head loss calculation equation of the filter was determined through experiments and theoretical analysis and the head loss coefficient value was calculated. The relatively small error between the values predicted by the model and the measured values indicated that the prediction model obtained based on our experiments had high accuracy. This equation can be used as the calculation equation for the head losses of pre-pump micro-pressure filters under conditions with clean water.

At present, the filter head loss models established by domestic and foreign scholars through physical experiments and dimensional analysis methods are all obtained under the strong pressure boundary behind the pump. The head loss will also change. This article gives the head loss model under the conditions of pre-pump micro-pressure under the clean water condition. It has been verified to have a certain accuracy, which enriches the prediction of the filter head loss model, and also gives the impact on the clean water conditions. The order of the factors of filter head loss is flow rate, water separator type, and filter screen area.

CONCLUSIONS

Clean water hydraulic performance tests of a pre-pump micro-pressure filter were carried out, and the order of the degree of influence of the factors on the head loss was determined through analysis of variance, which was flow rate > water separator type > filter screen area. Dimensional analysis combined with a multiple linear regression was used to establish a clean water head loss prediction model, and the coefficient of determination (R^2) was 0.987. The predicted value of the head loss was compared with the measured value and the model was verified using reserved data. The maximum relative error of the prediction was 13.11%, and the minimum relative error was 0.56%. Our model could predict the clean water head loss accurately. The results obtained in this study are only applicable to flow rate (2–8 m^3/h), water separator type (not used, Type 1, Type 2, Type 3), filter screen area (1,105, 1,582, 2,060 cm^2), and other working conditions need to be further improved. This test only discusses the influence of flow rate, water separator type and filter screen area on the head loss of the pre-pump micro-pressure filter under clean water conditions, while the head loss and filtration performance of the filter under turbid water conditions need to be further studied.

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CONFLICTS OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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