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ORIGINAL PAPER

Influence of fine particle size and concentration on the clogging of labyrinth emitters

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Abstract The evolution of drip emitter clogging with labyrinth channel was investigated experimentally to study the fine particle size and concentration effects in the irrigation water. Short-term clogging tests were performed using muddy water containing particles with 8 different sizes (all less than 0.1 mm). The particles used in this study were composed of fine sands, slit and clay. Afterwards, verification tests were conducted to prove the results obtained from short-term clogging tests. The impacts of particle size and particle concentration in muddy water on emitter clogging were analyzed by means of calculating the mean discharge and the Christiansen uniformity coefficient. The results showed that for particles that were smaller than 0.1 mm in diameter, sediment concentration significantly affected clogging. The clogging level of emitters increased with raising the concentration. Especially when the sediment concentration was higher than 1.25 g/L, the impacts became remarkable. On the other hand, the sensitive sediment particle range that could get emitters clogged easily was found. In this study, the sensitive particle range were D6 (0.038–0.034 mm) and D7 (0.034–0.031 mm) The results aim to help in improving drip irrigation methods using water with high sediment concentration and providing experimental data for optimization design of emitter channel.

Introduction

The clogging of emitters is a major problem affecting the lifespan and performance of drip irrigation systems. Since the first international conference on drip irrigation was held in Israel in 1971 (Yao et al. 2011), numerous attempts on solving clogging problems have been conducted (Bucks and Nakayama 1979; Nakayama and Bucks 1991; Mu et al. 2007; Duran-Ros et al. 2009). The proposed methods include rational filtering, chlorination and acid injection, as well as optimization of the structural design of emitter channels. However, the problem has still not been satisfactorily solved.

Physical clogging caused by solid particles are considered as the most common plugging form of emitters (Nakayama and Bucks 1991; Pitts et al. 2003), and also the direct reason that leads to emitter clogging (Yan et al. 2009). The water used for drip irrigation system in the Northwest China area mainly comes from local rivers and canals. The residual solid particles with diameter less than 0.075 mm can still enter the emitter channel although the irrigation water has been filtrated by a combination method of sedimentation, grit filtration and mesh screen (Qian 2002). Therefore, many studies have been conducted on the emitter clogging using irrigation water with certain solid particle concentrations (Capra and Scicolone 2007; Wei et al. 2008a, b). Since the characteristic scale of the labyrinth channel width is mostly around 1 mm (Zhang et al. 2010), the majority of researches are focused on clogging

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problems induced by solid particles with diameters around 0.1–0.25 mm, which is approximately 1/7–1/3 of the channel width, using the clogging test with muddy water (Haman et al. 2003; Duran-Ros et al. 2009). However, for the particle sizes less than 0.08 mm, few experiments are carried out except some studies using CFD methods attempt to predict the clogging evolution. The numerical studies have shown that the main factors affecting clogging are the velocity of suspended particles, particle diameters, and sediment concentrations (Wei et al. 2008a, b; Liu et al. 2010). The possibility of emitter clogging is dramatically increased at particle diameters larger than 0.05 mm (Wei et al. 2008a, b). In terms of fine particle diameter range (diameter <0.01 mm) that causes clogging, experimental validation data are lacking. In addition, once the particle size is small enough, a series of microscopic hydrodynamic phenomena may occur, such as aggregation, cementation, and transport which results in the formation of flocs and further deposit in the emitter. It is reported that the accumulation of such flocs becomes the major reason of the decline of the flow rate of the emitter (Wu et al. 2008). Unfortunately, these processes can hardly be simulated with software.

In the present paper, the effects of particle size and concentration in muddy water on emitter clogging with labyrinth channel were investigated. The short-term anti-clogging experiment was used to determine the sensitive ranges of particle diameters and sediment concentrations that cause different clogging levels. Afterwards, verification tests were conducted to further prove the results obtained from the short-term clogging tests. The results aim to help in improving drip irrigation methods using water with high sediment concentration and providing experimental data for optimization design of emitter channel.

Materials and methods

Experimental setup

The experimental setup is shown in Fig. 1. The testing device consists of the particles and water mixing tank, the automatic pressure control system, the computer, the real time water weighing system and the testing platform, etc. The particles and water mixture tank is a cylindrical container with 2 m in circumference and 0.5 m in height. A drain valve is installed at the bottom of the tank for flushing after each test. Muddy water is pumped into the drip tape by a submersible pump in the tank which has a rated lift of 45 m and discharge of 1.37 m^3/s. The backwater pipe is connected to the inlet pipe of the pump so that the backwater can be pumped into the system again. The pipe has punched holes with 6 mm in inner diameter every 8 cm,

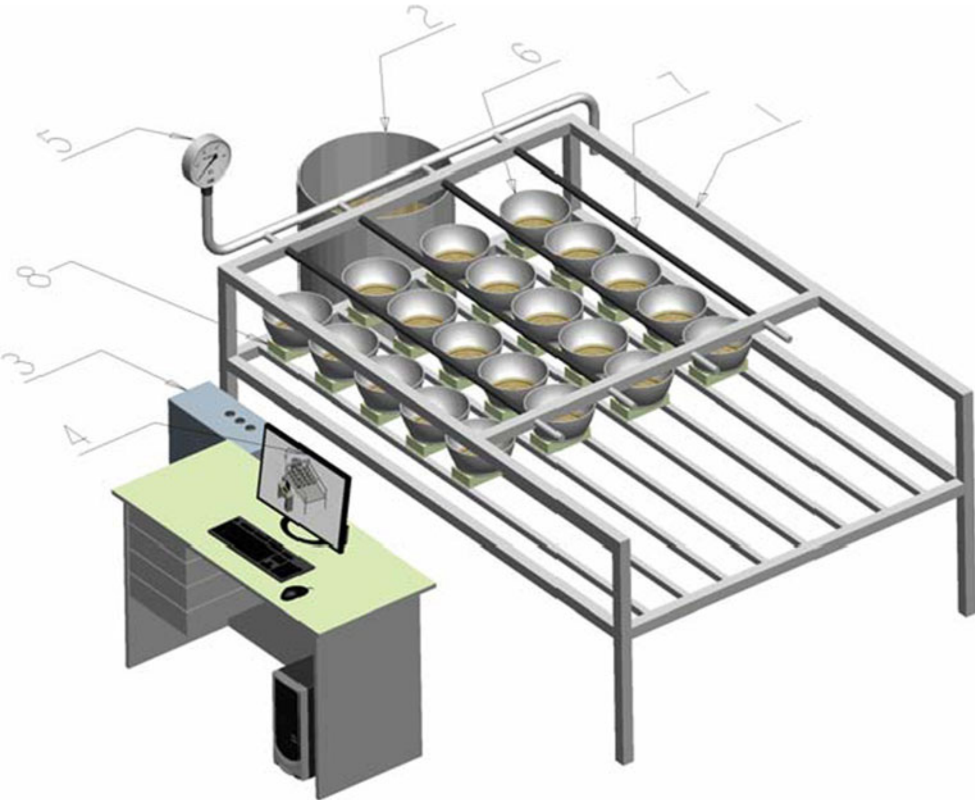


Fig. 1 Schematic diagram of the experimental setup. *1*-Test platform, *2*-particles/water mixing tank, *3*-convertor, *4*-computer, *5*-manometer, *6*-water collector, *7*-drip irrigation taper, *8*-flow weighing device

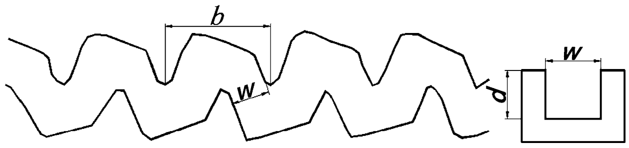


Fig. 2 Flow path structure of emitters. Channel tooth space $b = 2.3$ mm, channel width $w = 1.0$ mm, channel height $d = 0.8$ mm

and it is blocked at one end. This setup allows for the thorough mixing of water and particles by the jetting action of the backwater pipe. Meanwhile, the muddy water is stirred continuously manually to make sure the concentration is uniform everywhere in the tank. The measure range of manometer gauge is from 0 to 0.16 MPa, and the precision is 0.002 Mpa. The pressure can be remote controlled and monitored using the computer. The frame of testing platform is made of stainless steel tube. Four pairs of nozzles are installed in the platform to supply irrigation water. And four parallel drip irrigation tapes are installed in the platform. Each of the four tapes contains 5 emitters with the spacing of 0.3 m. There are a total of 20 emitters involved in the setup. Under each emitter, outflow collector mounted with weight sensor is placed to weigh the water coming out of the emitter. The flow weight data are converted to the flow discharges and transferred to the computer in real time. The range of the weight sensor is 1,800 g with an accuracy of 1 ‰. However, during the experiments, 2 weight sensors under a lateral tape did not work. So that tape was excluded and a total of 15 emitters were calculated.

The drip tape has an external diameter φ of 16 mm, a wall thickness of 0.28 mm, an internal diameter of 15.44 mm, a rated pressure P of 0.1 Mpa (10 m water head), and a rated flow q_0 of 3 L/h. The structural parameters of the labyrinth emitter are: the channel width w is 1.0 mm, the channel height d is 0.8 mm, the channel tooth space b is 2.3 mm, the flow path length L is 300 mm, and the number of channel tooth n is 14. The schematic of the flow path is shown in Fig. 2. After tested with freshwater, the flow coefficient k of each emitter is 0.301, and the flow stance index x is 0.53.

The water used in the experiment is tap water. The quality of the experimental water measured by Geological Bureau of Shaanxi Province is indicated in Table 1, which accord with the water quality standards of irrigation in China (GB5084-2005/Chinese Standards 2005). The pH value is 7.54. TDS, SO_4^{2-} and the total hardness are high, which suggests the salinity is relatively high. Ca^{2+}, Mg^{2+} exist in the steady forms of polythionate, nitrate and chloride and therefore, they could not be removed by heating. The bacterial population measured is 0, so we neglected the effect of microbes to clogging.

The soil used was air-dried and all the particles sizes were less than 0.10 mm. To study the effect of particle sizes on emitter clogging, the soil was screened into 8 parts containing particles with different sizes using corresponding mesh screener, see Table 2. The methods included high-frequency oscillation grinding, processing and sifting. Since in practice the actual mean maximum sediment concentration of irrigation water was about 0.8 g/L, the

Table 1 Quality of tap water in the experiment

Source	COD_{Mn} (mg/L)	pH (mg/L)	TDS (mg/L)	TSS (mg/L)	Fe (mg/L)	Mn (mg/L)	SO_4^{2-} (mg/L)	Total hardness (mg/L)	Bacterial population (cfu/mL)	EC (μs/cm)
Tap water	0.48	7.54M	1,090M	0S	0.094S	<0.05S	284	520	0S	1,295

COD Chemical oxygen demand, *TDS* total dissolved solids, *TSS* total suspended solids, *EC* electric conductivity

According to the evaluating grade of water quality to emitter clogging by Bucks and Nakayama (1979), m, M and S in this Table indicate mild, Moderate and Severe water quality, respectively

Table 2 Sediment particle size distribution for each diameter range

Serial number	Diameter range (mm)	Particle size composition (Chinese system)		
		Fine sand (%) 0.1–0.05 mm	Silt (%) 0.05–0.005 mm	Clay (%) <0.005 mm
D1	0.075–0.1	85.89	3.68	10.43
D2	0.061–0.075	62.94	19.02	18.85
D3	0.058–0.061	71.21	5.97	23.02
D4	0.045–0.058	21.31	45.41	33.28
D5	0.038–0.045	30.2	56.66	13.14
D6	0.034–0.038	16.31	30.31	53.38
D7	0.031–0.034	14.61	32.35	53.04
D8	<0.031	10.68	28.74	60.58

muddy water concentrations studied for each diameter range were determined as 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75 and 2.0 g/L in this experiment. The pressure was maintained at 0.1 MPa (10 m water head).

Experimental measurements

The experimental measurements involved two parts. The first part determined the clog-causing ranges of particle diameters and sediment concentrations using short-term clogging tests. The second part verified the conclusions of the first part by using muddy water with mixed-particle-size. The experiment was conducted in Drip Irrigation Equipment R&D Laboratory in Northwest A&F University from February 20th to April 6th, 2011. During the experiment, the laboratory indoor temperature was 22–25°C. The water temperature was 22–25°C.

In practice, the irrigation duration is around 6–10 h and the intermission is about 2–6 days in Northern China. However, for laboratory study, it's too expensive and time consuming to follow the actual irrigation situation. Therefore, researchers proposed some methods for short-term clogging tests. According to clogging test methods for emitters (ISO 2003), the suggested operation period and intermission for short-time clogging test is 5–10 min and 5 min, respectively. Nevertheless, the method of testing emitter clogging is still under discussion. In this study, the short-term clogging test employed the procedure of short-term continuous adding sand, which basically followed the draft guildlines as recommended by clogging test methods for emitters (ISO 2003). However the irrigation duration and time intervals between each duration had been extended in order to approach the actual irrigation condition. As shown in Table 2, particles with 8 diameter ranges (D1–D8) were screened to conduct this test. To clearly explain the procedure of the test, an example is taken as follows: for D1 (0.075–0.1 mm), firstly pre-made muddy water with 0.25 g/L concentration containing fine solids with diameter range of 0.1–0.075 mm was added to the particles and water mixture. The operation pressure was set at 0.1 MPa in the computer, and the "Start" button was clicked to remote-start the pressure control system. Meanwhile, the pump in the particles and water mixing tank was turned on to pump water into the experimental system. Once the pressure reached the rated value, the flow weighing system started up automatically and transferred the real-time data of the flow discharge. This irrigation process lasted about 30 min. After that, a 6 h intermission was taken in order to let particles deposit. For convenient description, the whole process of a 30 min operation and a 6 h intermission was named as one RUN. After the first RUN, the pre-made muddy water with 0.5 g/L concentration with the same diameter range (0.1–0.75 mm) was added to the tank. And another 30 min operation and 6 h intermission started (Second RUN). In the same way, the concentration was increased by 0.25 g/L for the following RUN until the muddy water concentration reached 2 g/L. Thus, a total of 8 RUNs were involved. For particles with other diameter ranges, the whole procedure was completed like D1. Before new particle sizes were added, the test system was thoroughly rinsed with fresh water to eliminate the effect of other diameter particles. In this study, each individual test lasted 52 h or approximately 3 days. Hence, the entire sets of experiments were conducted for about 24 days. Afterwards, according to the results of the short-term clogging tests, these 8 kinds of particle sizes were classified into 3 clogging levels: (1) difficultly clogged (DC), (2) easily clogged (EC), and (3) very easily clogged (VEC). The details about which diameter ranges were selected in which level will be explained in the latter section.

Considering the possible collision, adhesion, cohesion and separation interactions among different particle sizes, the verification experiments were carried out for each clogging level. To strengthen the comparison of the test results, the concentration of particles was made lower if they were easier to block the emitters, and vice versa. For DC (Difficulty Clogged) level, the muddy water concentration was made to 2.0 g/L. All diameter ranges involved in this level were selected and weighed equally (mass ratio = 1:1:1 :…). Similarly, for EC (Easily Clogged) level and VEC (Very Easily Clogged) level, the muddy water concentration was set to 1.5 and 1.0 g/L, respectively. The system pressure was controlled at 0.1 MPa. Just the same as the short-term test, one RUN included a 30 min operation and a 6 h intermission. For the verification experiment, a total of 22 RUNs were performed for each clogging level. The entire set of experiments took 429 h, or approximately 21 days.

Evaluation parameters

For convenient description, some indexes are shown as follows:

The discharge of each individual emitter was denoted as q_i, where $i = 1$–15. Mean discharge $\bar{q}$ was defined as the arithmetic mean value of the discharges of the 15 emitters. The mean discharge was calculated for every RUN of each diameter range. The relative emitter discharge q_r was defined as the ratio of the mean discharge q at the end of the last RUN to the rated discharge q_p of this kind of emitter at rated pressure 0.1 MPa. A relative discharge less than 75 % was determined as the criterion for severe emitter clogging (ISO 2003). The outflow variation Δq_i (g/L) was defined as the discharge difference between two consecutive RUNs. The percentage of clogged emitters was the ratio of the number of clogged emitters to the total number of emitters in each experiment.

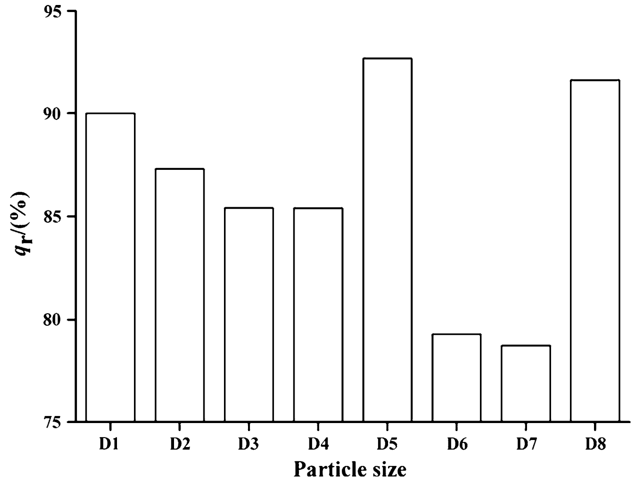


Fig. 3 Impact of particle size distribution on the relative flow

The Christiansen uniformity coefficient (Yao and He 1999) was calculated using the following equation:

$$\bar{q} = \frac{1}{n}\sum_{i-1}^{n} q_i \tag{1}$$

$$S_q = \sqrt{\frac{\sum_{i=1}^{n}(q_i - \bar{q})^2}{(n-1)\bar{q}}} \tag{2}$$

$$C_v = \frac{S_q}{\bar{q}} \tag{3}$$

where q_i is the discharge of the ith emitter, L/h; n is the number of emitters; $\bar{q}$ is the average discharge of the emitter under the same condition, L/h; S_q is discharge standard deviation; C_v is Christiansen uniformity coefficient.

The Christiansen uniformity coefficient C_v is an important parameter which indicates the irrigation uniformity. If the Christiansen uniformity coefficient C_v approaches to 1, it means that emitters in the irrigation system have relatively the same discharge, and the discharge distribution is uniform and consistent; while if the Christiansen uniformity coefficient C_v is small, it suggests the discharges vary from one emitter to another, or in other words, some emitters in the irrigation system do not work properly. In this experiment, because the clogging problem confined emitters' function, the Christiansen uniformity coefficient C_v is used for indicating the clogging level. The smaller the C_v is, the more likely emitters get plugged and the severer the situation is.

Results and analyses

Evaluation of emitter clogging

The relative emitter discharges q_r were calculated at the end of the last RUN for different particle sizes, to evaluate the clogging (Fig. 3). They were 90, 87, 85, 85, 93, 78, 77, and 92 %, respectively. A 75 % rated flow line was used as the criterion for emitter inefficiency or severe emitter clogging. As shown in Fig. 3, all the remaining discharges were above 75 %. None of the emitters were clogged severely. However, their drip irrigating functions were attenuated in different degree. Apparently, the relative discharge of D6 and D7 at the end of the 8th RUN reduced the most comparing with that of the other diameter ranges. Although the relative discharges for D6 and D7 were still above 75 %, the situation of emitter clogging was worse and the emitters might lose their dripping function very fast with time going by. Regarding to D1, D5 and D8, the relative discharges remained around 90 % of the rated discharge, and the other three diameter ranges, D2, D3 and D4, maintained at about 85 %. Table 3 showed the statistics on emitter clogging at the end of the clogging tests. The total number of emitters that got plugged for the whole set of experiments were 120 (15 × 8), and four of which had flows that decreased gradually and reached 0, which means complete clogging, eventually. There were 14 emitters that had flows decrease gradually and partial clogged at the end. Given that sediments with small particle sizes were used, suddenly and completely clogged emitters were not found.

All drip tapes were opened after being dried out to observe the clogging locations Fig. 4 depicted the deposition sites of the sediment particles in the labyrinth emitters. Table 3 showed the statistics on the process and location of sediment deposition.

As can be seen, emitter clogging generally occurred at the inlet and channel corners. In contrast, clogging at the outlet was relatively less. Based on the total number of emitters involved (120), the probabilities of clogging at inlet, corner and outlet locations were 7.5, 6.67, and 0.83 %, respectively. The reason why the inlet and corners could easily get clogged might be because the flow velocity changed rapidly at these two places. Due to the sudden contraction of cross section from drip tape to emitter labyrinth channel, the flow velocity at channel inlet decreased

Table 3 Number of clogged emitters

Item	Process of clogging			Position		
	Gradual and complete	Gradual and partial	Sudden and complete	Inlet	Corner	Outlet
Number of emitters	4	14	0	9	8	1

Fig. 4 Clogging of labyrinth channels

Complete clogging at inlet

Partial clogging at corner and inlet

Complete clogging at corner

Partial clogging at corner

suddenly. The muddy water could not carry the same amount of particles anymore and resulted in particles deposited at inlet area. In terms of the corners, flow often encountered a circulation zone at upstream corner area. At that area, the velocity and pressure were low so that particles were hard to get out but easily deposited and accumulated. From the particles' side, surface forces were relatively high for these fine particles with diameters less than 0.1 mm. When moving with water, some particles interacted and adhered with one another, resulting in flocs forming and gradually growing bigger. At the end of each operation RUN, 6 h' intermission allowed particles and formed flocs depositing in the channel. After several RUNs, some particles and flocs were carried away by water; while some of them accumulated and cemented into bigger particles or flocs and adhered to the channel wall and further blocked the flow channel. Since most of the particles were blocked at the channel inlet and deposited at channel corners, a small portion reached the outlet location. Meanwhile the flow rate was relatively low at the channel outlet, the chance of collisions and interactions between particles decreased, which restricted the development of flocs (Duffadar and Davis 2008). Particles sedimentation at outlet followed the process in the still water. In addition, the outlet is the place connected to the outside so that particles could be easily got rid of the emitter by the pressure difference.

Influence of particle diameter on emitter clogging

The mean emitter discharges and the Christiansen uniformity coefficients for each RUN of solid diameter ranges were calculated to analyze the particle influences (Fig. 5). The results showed that the mean emitter discharges generally decreased from the beginning to the end with increasing sediment concentration. In other words, emitters were gradually clogged in different degrees. However, as we can see from Fig. 5a, the slops of mean discharges changing were quite different, which suggested that the speed of clogging for different diameter ranges varied. Regarding to D8 (<0.031 mm), the decreased amplitude of flow was only 8.4 % at the end of the 8th RUN comparing with the beginning discharge; while for D7, the flow rate decreased by 21.3 % even at the 7th RUN. Yet, with respect to some other diameter range (D2), the discharge declined at first and then recovered a little bit at the end, indicating that the oscillating procedure of "blocking-flushing" occurred back and forth during the latter process.

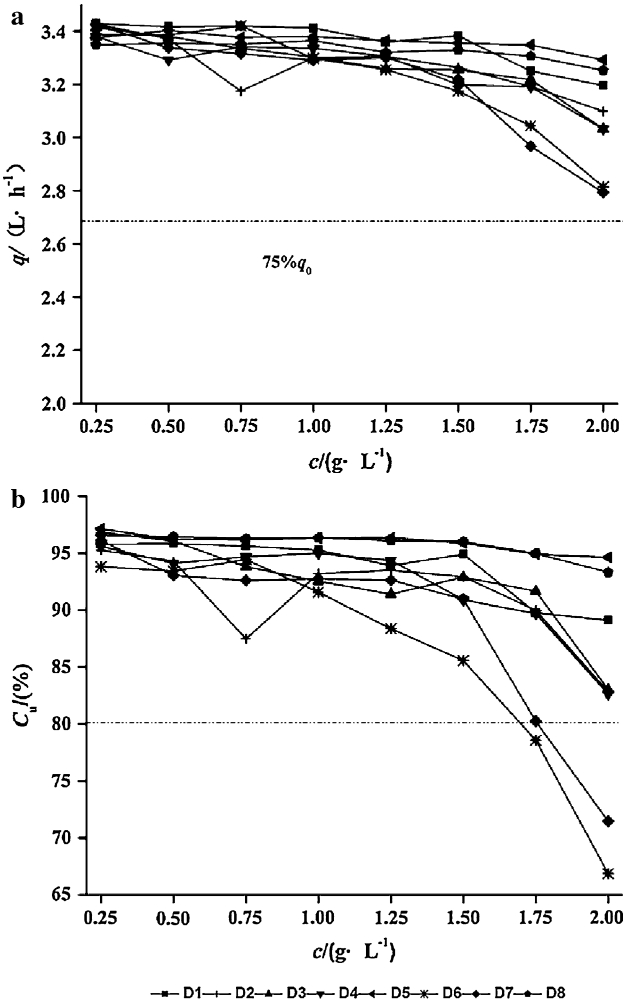


Fig. 5 Changes in mean emitter discharges and *Christiansen* uniformity coefficients (C_v) for each RUN of different solid diameter ranges. **a** Changes in mean emitter discharges, **b** changes in C_v

Table 4 Classification of clogging levels

	Difficultly clogged (DC)	Easily clogged (EC)	Very easily clogged (VEC)
Diameter (mm)		D1 = 0.1–0.075	
	D5 = 0.045–0.038	D2 = 0.075–0.061	D6 = 0.038–0.034
	D8 = <0.031	D3 = 0.061–0.058	D7 = 0.034–0.031
		D4 = 0.058–0.045	

In terms of Christiansen uniformity coefficient C_v, it is an index which indicates the discharge distribution for a group of emitters or clogging level. As for each single emitter, the clogging might have randomness. The discharge variation of single emitter might not fully represent the whole picture of the clogging degree of the irrigation system which in reality is most concerned. According to the clogging test results, the changes in Christiansen uniformity coefficient C_v with sediment particle size were plotted in Fig. 5b. Generally, the Christiansen uniformity coefficient C_v had a similar trend as the mean discharge variation but with different changing slop. Concerning D5 and D8 in Fig. 5, both mean discharge and uniformity coefficient decreased mildly which suggested that these particle sizes could pass the channel relatively smoothly or might be carried out of the channel for the next RUN and be hard to get emitters clogged. However, regarding to D6 and D7, both mean discharge and uniformity coefficient declined rapidly. Especially for C_v, the magnitude of decrease was about 29.12 % at the end of the last RUN which indicated that these particle sizes could easily block or deposit in the flow channel and afterwards got emitters plugged. While for the other particle sizes, D1, D2, D3, D4, the clogging situation seemed to be neither as severe as D6 and D7 nor as mild as D5 and D8, so that defined as moderate.

For better understanding, the relationship between the relative emitter discharge q_r and sediment particle diameter D1–D8 was presented in Fig. 3. The impact of sediment particle diameter on clogging was neither monotonic increasing nor decreasing, but existed sensitive diameter ranges D6 and D7 that easily got emitters plugged compared with the others. In Fig. 5b, Christiansen uniformity coefficient C_v of D6 and D7 changed rapidly which suggested that the majority of emitters were plugged with such diameter ranges. Using the SPSS 17.0 software, variance analysis of the effects of particle size on the emitter clogging was performed.

The results showed that the relationships between particle diameters and drip emitter clogging were significant ($P < 0.001$). Based on the above analysis, the classification of clogging levels were determined by means of the method of K-Means cluster analysis The results indicated that particle diameters D6 and D7 were Very Easily Clogged, denoted as VEC, D5 and D8 were Difficulty Clogged, denoted as DC, and D1–D4 were Easily Clogged, denoted as EC (See Table 4).

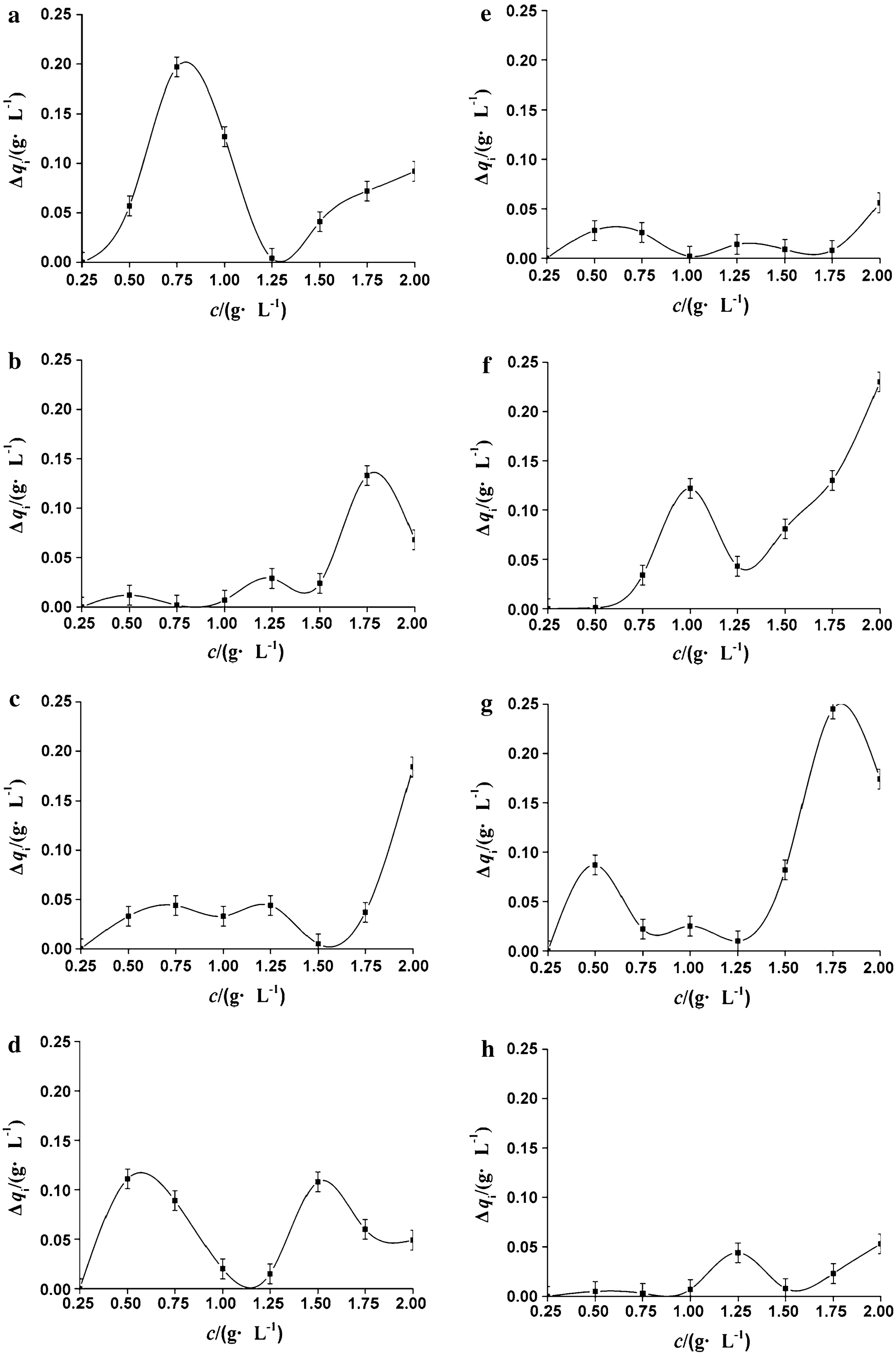
Influence of sediment concentration on emitter clogging

The variation of outflow discharges of each experimental RUN was analyzed using the dual factorial variance analysis of the Origin 8.0 software. Sediment concentration was significantly related to the clogging flow discharge variation of the emitters ($P = 0.00108$). In other words, fine sand muddy water sediment concentration significantly affected emitter clogging. Figure 6 showed the outflow discharge variation of emitter with different sediment concentration for each diameter range. The results indicated that with increased sediment concentration, the discharge differences increased generally. But the trend was oscillating. When the muddy water sediment concentration was 0.25 g/L, the variation reached 0 suggesting this concentration had litter effect on clogging. When the concentration increased to 0.5–1.25 g/L, there were moderate changes in the quantities of outflow discharge which implied clogging occurred in some emitters but the situation was not critical. For this diameter range, some deposited particles may be carried out of the channel during the next operation RUN. When the concentration rose to 1.25 g/L or higher, the clogging situation got so severe that outflow discharge varied tremendously indicating that most of the emitters were plugged. With concentration increasing, the possibility of collision and interaction among parcels enhanced and the particle sedimentation got thicker as well. Therefore, particle diameter significantly affected the clogging of drip irrigation emitters. The outflow discharge variations of diameters D5 and D8 gently changed with 0.045 fluctuations. In contrast, the variation of diameters D6 and D7 dramatically changed with a fluctuation of around 0.245. Thus, with increased sediment concentration, D6 and D7 caused clogging very easily. The results were consistent with the previous classification in the previous subsection.

Verification results

Figure 7 showed the changes in average emitted discharge under different irrigation RUNs. Figure 7a showed that the DC group did not easily clog, even at high muddy sediment

Fig. 6 Emitter flow discharge variation with different sediment concentration for each diameter range.
a D1 = 0.75–0.1 mm,
b D2 = 0.061–0.075 mm,
c D3 = 0.058–0.061 mm,
d D4 = 0.045–0.058 mm,
e D5 = 0.038–0.045 mm,
f D6 = 0.034–0.038 mm,
g D7 = 0.031–0.034 mm,
h D8 < 0.031 mm



concentrations (2.0 g/L). At low concentrations of muddy water (1.0 g/L), the VEC group had greater discharge reduction and more severe clogging than the EC and DC groups. The average emitter discharge of the EC and VEC group remarkably decreased after the 6th RUN, and the discharge decreased below 75 % of the rated discharge at the 16th RUN. However, for the DC group, the discharge started to decline at the 11th RUN and was still above 75 % of the rated discharge at the end of the last RUN. The emitters remained unclogged until the end of the experiment, thereby displaying a very good anti-clogging performance.

Emitter clogging resulted in small Christiansen uniformity coefficient C_v. Figure 7b showed decreased C_v with

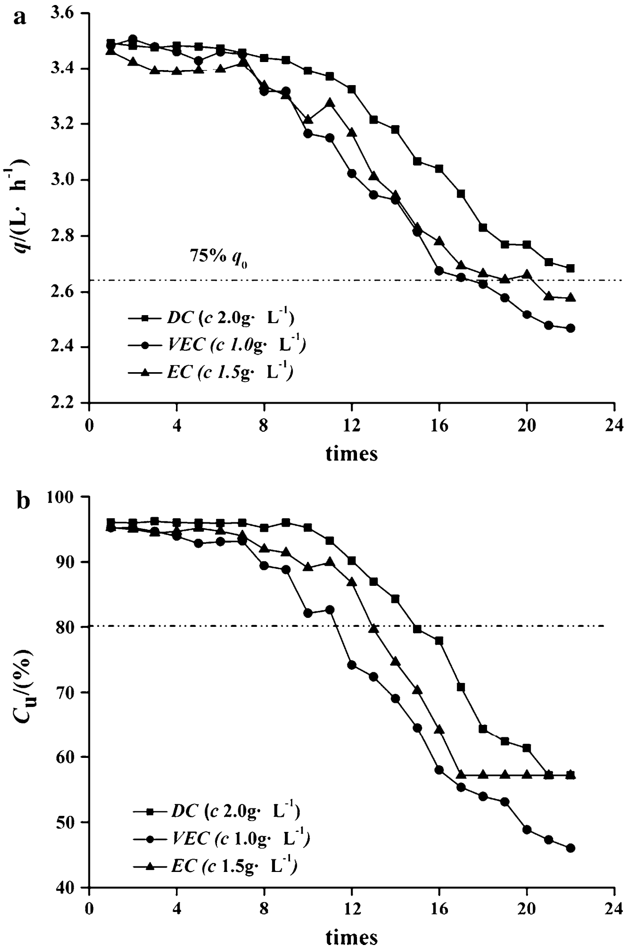


Fig. 7 Changes in average emitter discharge under different irrigation times. **a** Changes in mean emitter discharge, **b** changes in C_v

increased irrigation RUN. For DC group with high concentration, Christiansen uniformity coefficient C_v remained above 80 % after the 14th RUN. However, for VEC group with low concentration, the irrigation uniformity was under 80 % at the 10th irrigation. These results proved that the sensitive sediment particle range that could get emitters clogged easily did exist. In this study, the sensitive particle range were D6 (0.038–0.034 mm) and D7 (0.034–0.031 mm)

Discussion

A previous numerical simulation approach indicated that clogging did not easily occurs when the particle diameters were 1/10–1/6 of the least channel width. And the probability of clogging was positively correlated with particle sizes (Wei et al. 2008a, b). When particle diameters were larger than 0.05 mm, the coefficient of emitter clogging rapidly increased (Zhang et al. 2010). The present paper found slightly different results from the numerical simulation. The discrepancies were attributed to the fact that the numerical method cannot simulate the process of the flocculation of fine particles. Instead, the numerical method most focused on turbulent gravity sedimentation. When the particle diameter approached relatively large value (e.g. D1–D4), the primary forces that caused clogging were particle collisions, sedimentation, and accumulation. When the particle diameter was small, surface tension and its adhesion with surrounding substances became the major forces that caused clogging. In conclusion, when irrigated with muddy water that contain large particles, the particle diameter is the most important factor affecting the clogging of a labyrinth emitter (Duran-Ros et al. 2009; Qian 2002). This study used particles less than 0.1 mm in diameter. A certain concentration of sediment was necessary that caused particle collision and flocculation. The distribution of particle concentration in the channel increased when the sediment concentration rose (Wei et al. 2008a, b). When the sediment concentration reached a certain level (~1.25 g/L), the particle concentration had a notable effect on emitter clogging.

Emitter clogging caused by fine particles is divided into flocculation of cohesive particles and deposition of non-cohesive particles. For particles ranging from 0.045 to 0.1 mm in diameter (D1–D4), the emitter clogging increased with decreased particle size. As shown in Table 2, when the content of cohesive particles increased from 10.43 to 33.28 % (D1–D4), the flocculation significantly enhanced. The main component of the particles with diameters of 0.045–0.038 mm (D5) was silt, and the content of cohesive particles was only 13.14 %. Therefore, the flocculation of cohesive particles can be neglected. Zhiping Li et al. suggested that for particles less than 0.075 mm in diameter, the velocity differences between the particles and water were very small. They indicated the particles' following behaviors with water were close to 1 (Manning et al. 2010), which means the velocity of sediment particles coincided with the fluid velocity. Thereby, these particles could easily flow out with the water. However we found a sensitive diameters ranging from 0.031 to 0.038 mm could cause emitter clogging easily. There were two reasons. First, collision and deposition in the vortices of the flow easily occurred because of the small sizes and the large drag force of the particles. Consequently, the particles failed to escape from the vortices. Second, because the composition of particle sizes was relatively complex, the interactions among fine sand, silt, and cohesive particles resulted in the hiding and exposing action, which was the hiding affect, produced by the larger particles to the smaller particles. Thereby, the smaller particles got less dragging forces and that the larger particles suffered more forces of water. The startup of particles needed to get over the extra forces due to the interactions among the course and fine particles (Jha and Bombardelli 2011). The particles accumulated and formed larger size aggregates. Subsequently, blockages in the drip emitters were created.

In summary, when the irrigation water has a high sediment concentration, precipitation measures should be taken to perform preliminary treatment for water quality and to avoid emitter clogging. This method eliminates general suspended solids in the water and reduces the load of one-stage filter. After that, use the combination of grit filter and granular filter to filtrate suspended particles, as far as possible to filter out sediment particles more than 0.1 mm. For the particles between 0.03 and 0.04 mm, due to incapable of filtering, we should extend the precipitation time of the irrigation water and clean the capillary vessels promptly. Instead, at the beginning or the end of irrigation, we can properly increase or decrease the pressure to change the velocity of water in the emitter to effectively prevent clogging.

Conclusions

The present paper examined the variations of muddy water discharges and emitter clogging caused by particles less than 0.1 mm in diameter. The working pressure was fixed at 0.1 MPa, and 8 different sediment concentrations of muddy water (0.25–2.0 g/L) were used. Short-term clogging tests and verification experiments were performed. The following conclusions were drawn.

First, fine particles caused labyrinth emitter clogging at similar locations as large particles, which generally occurs at the inlet and corners of the flow channel.

Second, sediment concentration and particle sizes are primary factors affecting emitter clogging. When particle diameters are less than 0.1 mm, sediment concentration is significantly related to emitter clogging ($P = 0.00108$). If the irrigation time is short, sediment concentrations less than 1.25 g/L do not significantly affect the clogging of emitters. When the sediment concentration is larger than 1.25 g/L, particles in the channel deposit frequently and discharge varies strongly. The possibility of clogging rapidly increases at sediment concentrations of 1.25–1.5 g/L.

Third and last, under uniform water quality conditions, sensitive sediment particle range that could get emitters clogged easily was found. In this study, the sensitive particle ranges were D6 (0.038–0.034 mm) and D7 (0.034–0.031 mm). For these fine particles that are hard to remove during filtration, special anti-clogging techniques of the irrigation systems should be taken to reduce the blocking of emitters.

There were some limitations on the experimental conditions in the present study. The limitations were the test times, combinations. The clogging mechanism of labyrinth channels in emitters needs further study.

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