doi:10.6041/j.issn.1000-1298.2016.02.014

Influence of Temperature on Emitter Clogging with Fertigation through Drip Irrigation Systems

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Abstract: Fertilizers injected into a drip irrigation system may contribute to serious clogging, which occurred as a result of multiple factors, including water quality, water condition, hydraulic parameters and system design. To better understand the causes and process of the emitter clogging with fertigation at different levels of irrigation water temperature, laboratory experiments were conducted to measure the effects of irrigation water temperature on the sensitivity of the emitter clogging in the Institute of Water-saving Agriculture in Arid Areas of China, Northwest A&F University. Three different particle gradations and three different fertilizer concentrations were investigated through the intermittent drip irrigation method in summer and winter. Experiment results showed that the temperature of irrigation water was an important factor affecting clogging, with a remarkable coupling effect with water quality. The anti-clogging performance of emitters in summer was always better than that in winter for both scenarios with fertilization and no fertilization. The acceleration of drip irrigation system clogging with fertilization was affected by the sediment gradation and the season. When the content of sediment particles with size of 0.034 ~ 0.1 mm was increased, the fertilizer concentration affected clogging more sensitively in winter than in summer. The fertilizer concentration affected clogging more sensitively in summer than in winter with increasing content of sediment particles with size of 0 ~ 0.034 mm. The number of effective irrigations in summer was 1.26 ~ 1.43 times of that in winter. However, the irrigation water temperature could not change the effect of sediment gradation and fertilization concentration on clogging. Therefore, it was recommended that irrigation frequency could be reduced when the irrigation water temperature remained low, and the fertilizer concentration should be controlled at a low level when irrigating with the integration of water and fertilizer.

Key words: emitter; clogging; temperature; fertilizer concentration; sediment gradation

0 Introduction

Emitter clogging is an important factor that affects the irrigation performance and service life of drip irrigation systems, and it is also a research focus in the drip irrigation technology field. Based on the cause, emitter clogging is classified into three types: physical, chemical and biological cloggings[1]. In practice, clogging is often caused by a combination of the aforementioned three factors. Filtered irrigation water retains fine sediment particles[2], which enter the labyrinth channels and gradually clog the emitters. Studies[3-5] showed that emitters with different structures might differ in the particle size range and grades that they are easily clogged by. Therefore, emitter clogging can be controlled by filtering or depositing sediment particles of a certain size or within a specific range in the practical irrigation water. In addition, irrigation water always contains chemically soluble matter and microbial communities. Regarding the chemically soluble matter, the physical and chemical processes (e.g., replacement, crystallization, and deposition) associated with calcium, magnesium and phosphorus ions can also promote emitter clogging. It is generally agreed that the more alkaline the irrigation water is, the greater the probability is that the irrigation water causes chemical clogging of the emitters[6-8]. The growth of

Received date: 2015-09-06 Accepted date: 2015-11-29
Supported by "the Twelfth Five-year" National Key Technology Support Program (Grant No. 2015BAD24B01) and National Natural Science Foundation of China (Grant No. 51379024)
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microorganisms and the formation of biofilms in the irrigation water will promote the bonding and deposition of physical and chemical particles and represent further important factors that induce emitter clogging[9-10]. In addition to the aforementioned three water quality-related factors, the hydraulic parameters of the emitters and drip irrigation system operation and management also affect emitter clogging[11-12]. The effect of irrigation water temperature discontinuity on emitter clogging has rarely been investigated.

Due to differences in irrigation seasons and areas, and large variations of irrigation water temperature, studying the effect of irrigation water temperature on emitter clogging has important significance for irrigation management strategies that are used in different areas and different seasons. Increases of temperature increase the probability of particle collisions, promote the formation of flocculation and increase the level of chemical precipitation, thus exacerbating emitter clogging to some extent. However, increases of temperature increase the thickness of the electric double layers of sediment particles, decrease the viscosity coefficient of water, inhibit the growth of microorganisms, and reduce the capturing effect of biofilms. Consequently, in practice, increases of temperature actually enhance the anti-clogging performance of emitters[6, 13-14]. Niu et al.[11] studied the effect of irrigation water temperature and sediment particles with size less than 0.1 mm on emitter clogging and found that increase of temperature enhanced the anti-clogging performance of emitters. Hills et al.[6] investigated the effect of temperature on chemical clogging and found that increase of temperature promoted the deposition of calcium carbonate and magnesium carbonate, and exacerbated emitter clogging. However, because it is relatively difficult to accurately control irrigation water temperature, no definite conclusions have been drawn so far on the effect of temperature on emitter clogging caused by factors such as irrigation water quality and channel structure. In addition, with the rapid development of fertigation technology, clogging caused by fertigation employed in drip irrigation has attracted increasing attention[15-16]. Cations in the fertilizer will affect particle flocculation[17]. Further research is needed to understand how irrigation water temperature affects particle flocculation and the mechanism that temperature, sediment, and fertilizer collectively affect emitter clogging.

Therefore, inner inlaid emitters with labyrinth channels were selected as experimental emitters; and experiment was conducted with intermittent muddy water irrigation for fixed periods in summer and winter (large water temperature difference existed between summer and winter). Irrigation water samples with different sediment gradations and fertilizer concentrations (ρ) were prepared in laboratory to analyze the effect of irrigation water temperature on emitter clogging caused by fertigation technology. The results obtained will provide basis for formulating reasonable fertigation management strategies.

1 Materials and methods

1.1 Experimental materials and equipment

An inner inlaid drip irrigation tape with toothed labyrinth channels (manufactured by Yangling-Qinchuan Water Saving Irrigation Equipment Co., Ltd.) was used in the experiment. The main parameters of the drip irrigation tape when the working pressure is 40 kPa are as follows: rated flow of each emitter (q) is 2.3 L/h, pipe diameter is 16 mm, pipe wall thickness is 0.2 mm, number of grids at each emitter inlet is 8, channel width is 0.8 mm, tooth height is 1.1 mm, tooth spacing is 3 mm, number of channel units is 14, and manufacturing error of emitters is 1.76%. Groundwater in Yangling (pH value of 7.54, total number of bacteria of 0, hardness of 340 mg/L; number of suspended particles of 0 and conductivity of 650 μS/cm) was used in the experiment. A compound fertilizer (produced by Shanxi Jingsheng Fertilizer Industry Group Co., Ltd.) was used in the experiment which was mainly comprised of monoammonium phosphate, diammonium phosphate, ammonium sulfate, potassium sulfate and urea. The mass ratio of the nitrogen, phosphorus, and potassium contents of the experimental fertilizer was 1:1:1. To ensure that the fertilizer was completely dissolved, the compound fertilizer was dissolved in a glass beaker and fully mixed using a glass rod, and the solution was then allowed to stand for 1 h. Observations were later made to determine whether the fertilizer coating had settled or remained in suspension. Finally, the transparent liquid at the top was collected and added to the testing system. Yangling silty soil that had been sieved and washed with water was used as the experimental sediment. To eliminate interference by salt ions absorbed on the surface of the sediment particles in the experiment, the sediment was sieved through a 0.1 mm sieve and washed with clear water. The muddy water generated by the sieving process was collected, and the sediment particles in the water were allowed to settle down. The clear liquid at the top was then removed. The settled sediment was repeatedly washed, first through a 0.067 mm sieve and then through a 0.034 mm sieve. The sediment residues remained in the 0.034 mm sieve were collected. The sediment particles with size less than 0.034 mm were allowed to settle down; the clear liquid at the top was then removed. Water was then added to dilute the remained mixture. This process was repeated. Finally, the settled sediment was collected.

The anti-clogging test platform was constructed according to the Technical Specifications and Experimental Methods for Agricultural Irrigation Equipment—Emitters, the Industrial Standards of the People's Republic of China—Micro-irrigation Emitters, and the Draft International Standard for Anti-clogging Research[18] Regarding Tests on the Sensitivity of Clogging of Indoor Emitters. The experimental equipment comprised a variable frequency pressure device, an automatic data acquisition device, a water/sediment mixing device, and a clogging test platform. The variable-frequency pressure-regulating dial was controlled by a computer (control precision: 0.01 m water head). The data acquisition device was controlled by a computer to obtain real-time measurements using an electronic balance. The automatic data acquisition interval was set to 1 s. The data acquisition error was 0.2 g. The water/sediment mixing device comprised a water tank, a submersible pump, and a mixer. The muddy water was mixed homogeneously using the mixer. The test platform was equipped with four capillaries, and the distance between two adjacent capillaries was 30 cm. Each capillary had five emitters. The distance between two adjacent emitters was 45 cm. The test platform had a total of 20 emitters.

1.2 Experimental methods

The experiment was carried out in two stages. The first stage was carried out in winter (December 1, 2014—January 10, 2015), and the second stage was carried out in summer (June 3, 2015—July 5, 2015). Before each test, the temperature of the irrigation water was measured using a thermometer. The water temperature in winter had a minimum value of 3℃, a maximum value of 8℃, and a mean value of 5℃. The water temperature in summer had a minimum value of 19℃, a maximum value of 29℃, and a mean value of 23℃.

Three sediment grades, denoted A, B, and C, were designed. Each grade had a sediment content of 1 g/L (Tab. 1). To accelerate the clogging effect, three fertilizer concentrations (ρ = 1.0 g/L, ρ = 0.8 g/L, and ρ = 0.6 g/L) were designed. The condition in which no fertilizer was applied (ρ = 0) was used as the control. There were two irrigation seasons: winter and summer used in irrigation. There were a total of 24 treatments. Each treatment was repeated twice. Each time, four capillaries were laid out. Each capillary had five emitters. Two capillaries were used in each repeat, and there were four repeats. The mean flow at the outlets of the emitters was recorded after each irrigation was completed.

Tab. 1 Sediment particle size distribution %

Sediment grades	Proportions of particles of various sizes (diameter)		
	0 ~ 0.034 mm	0.034 ~ 0.067 mm	0.067 ~ 0.1 mm
A	56.12	24.16	19.72
B	14.21	58.34	27.45
C	20.27	19.47	60.26

An intermittent anti-clogging test method with fixed periods involving muddy water was used. The test pressure was 40 kPa. Irrigation was applied for 30 min each time, and the interval between irrigations was 4 h. After irrigation was completed, the flow of each emitter was recorded using a weighing sensor. The ratio of the mean flow of muddy water to the mean flow of clear water in each capillary (i.e., the mean relative flow, q) was calculated. When q was less than 70%, irrigation was terminated, the number of irrigations and the number of completely clogged emitters were recorded.

1.3 Evaluation indexes and method

According to the Technical Specifications for Micro-irrigation Engineering of China, serious clogging of emitter is considered to have occurred when the flow of emitter is less than 75% of the designed value[19]. The Draft International Standard for Micro-irrigation Systems Regarding Tests on Clogging of Emitters defines clogging of an emitter as follows: serious clogging of an emitter is considered to have occurred when the flow of the emitter decreased by 25% ~ 30%[18]. To increase the number of experimental results, the number of irrigations was increased appropriately. Therefore, a q-value of less than 70% of the initial flow was used as criterion to determine whether clogging occurred in the system. When $q <$ 70%, serious clogging was considered to have occurred in the overall irrigation system, irrigation was terminated, and the number of irrigations was recorded. Here, q can be calculated by using the following equation

$$q = \left(\sum_{i=1}^{n} \frac{q_i}{q_{pi}} \right) \Big/ n \qquad (1)$$

where q—mean relative flow, %

i—emitter number

n—total number of emitters

q_i—flow of muddy water at the i^{th} emitter, L/h

q_{pi}—flow of clear water at the i^{th} emitter, L/h

With the increase of number of irrigations, scouring and silting occurred repeatedly in the channels, and q exhibited a fluctuating and decreasing trend. An irrigation process with q of 70% or greater was considered an effective irrigation (for calculating the number of effective irrigations). The ratio of the number of clogged emitters to the total number of emitters was termed as clogging ratio.

2 Results and analysis

2.1 Effect of experimental parameters on clogging

Because the temperature of irrigation water was difficult to control, the irrigation water temperature was controlled by design within two ranges: 3 ~ 8℃ and 19 ~ 29℃. To discuss whether changes of irrigation water temperature within each range affected clogging, the temperature of the irrigation water was subjected to unifactorial analysis of variance (ANOVA) using SPSS 22.0 software. The results showed that there was a significant difference between the temperature range groups ($P = 0.021 < 0.05$), but no significant difference was found within the same temperature range group, indicating that the effect of temperature variations within the same range on clogging can be ignored. Then, the effect of each parameter on emitter clogging was further explored. The flow at each emitter was subjected to univariate multifactorial ANOVA. Duncan's multiple comparison model was used. The ANOVA results (Tab. 2) showed that the P values of the three factors ρ, sediment grade and irrigation water temperature were less than 0.05 at the confidence level of 95%, indicating that the effect of each factors on the emitters clogging reached high significance and the three factors importantly contributed to emitter clogging. However, the interaction between any two of the three factors did not reach significance ($P >$ 0.05). These statistical results, from another perspective, demonstrated that the interaction among

Tab. 2 Analysis of variance for total test data

Variance sources	Sum of squares	Degree of freedoms	Mean square	F value
Sediment grade	2.777	2	1.388	16.026**
Irrigation water temperature	0.770	1	0.770	8.887**
ρ	2.208	3	0.736	8.495**
Sediment grade × irrigation water temperature	0.010	2	0.005	0.059ns
ρ × sediment grade	1.436	6	0.239	2.763*
ρ × irrigation water temperature	0.109	3	0.036	0.418ns
ρ × sediment grade × irrigation water temperature	0.278	6	0.046	0.535ns
Error	6.237	72	0.087	

Notes: * and ** represent significant differences at $P < 0.05$ and $P < 0.01$ levels, respectively; ns represents non-significance ($P > 0.05$).

the factors within the same temperature range did not significantly affect emitters clogging and irrigation water temperature had complex antagonistic impact on the effect of ρ and sediment grade on emitter clogging.

2.2 Combined effect of irrigation water temperature and sediment grade on emitter clogging

Fig. 1 showed the changing trend of q of the emitters with the number of irrigations when muddy water consisted of three different sediment grades was used under different temperature conditions (no fertilizer applied).

For convenience of analysis, the changing process of q with the number of irrigations (n) was approximately fitted to a linear relationship

$$q = kn + b \tag{2}$$

where k is the slope of the $q-n$ relationship curve; b is the intercept on the ordinate axis.

k characterized the rate at which q decreased with n during the drip irrigation process using muddy water consisted of different sediment grades. The greater the absolute value of k was, the faster the clogging developed.

Based on Fig. 1, it can be seen that q was lower in winter than in summer and the decreasing trend of q with the increase of n was more significant in winter than in summer. The absolute value of k was the largest when sediment of grade B was used, and the absolute value of k was the smallest when sediment of grade C was used, indicating that emitter clogging occurred most easily when sediment of grade B was used and emitter clogging occurred more slowly when sediment of grade C was used. Under the same sediment grade condition, the extent of the opening between the two $q-n$ curves at different temperatures was the ratio of k values of the equations of the two curves. The decreasing trend of q in summer was gentler than that in winter. The k value in winter was 1.21 ~ 1.26 times of that in summer. The ratio of the k value in winter to the k value in summer (hereinafter referred to as the k ratio) was the highest when sediment of grade C was used, indicating that the effect of irrigation water temperature on emitter clogging was the greatest when the content of coarse particles (0.067 ~ 0.1 mm) was the greatest. In addition, the coefficient of determination (R^2) exhibited a decreasing trend with increase of content of sediment particles with size of 0.067 ~ 0.1 mm in both winter and summer; in general, R^2 was smaller in winter than in summer, indicating that at higher contents of sediment particles of size 0.067 ~ 0.1 mm, scouring and silting in the emitters was more significant during the interval between two successive irrigation periods, the clogging-cleaning oscillation occurred more frequently, and the randomness of the stage of the occurrence of clogging was greater. Similarly, the clogging-cleaning oscillation phenomenon was slightly more apparent in winter when muddy water was used for drip irrigation compared with that in summer; i.e., the change of q in summer was relatively smooth.

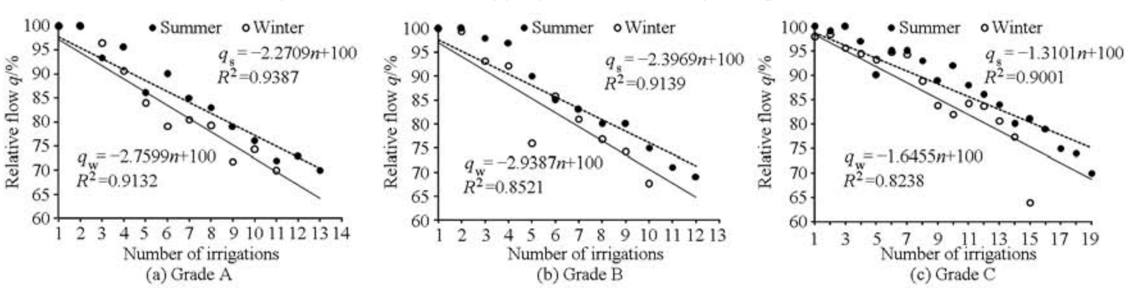

Fig. 1　Variation of relative flow change with irrigation frequency

It can be observed in Fig. 1 that the number of effective irrigations was higher in summer than in winter. At smaller absolute k values, the increase in the number of effective irrigations was greater. The number of effective irrigations was increased in summer by two times (compared with values in winter) when sediment of grade B which could easily cause clogging was used, and it was increased by five times when sediment of grade C which could not easily cause clogging was used. The total number of effective irrigations in summer was approximately 1.26 times of that in winter. Thus, drip irrigation using water at higher temperature significantly increased the number of effective irrigations. However, irrigation water temperature did not alter the size range of sediment particles that easily caused clogging. In both winter and summer, clogging occurred most easily when sediment of grade B was used and occurred with the most difficulty when sediment of grade C was used.

2.3 Combined effect of irrigation water temperature and ρ on emitter clogging

Fig. 2 showed the changing trends of q of emitters with n under different ρ values when muddy water was used for drip irrigation. Based on Fig. 2, it showed that the k ratio was decreased with the increase of ρ (from 0.6 g/L to 1.0 g/L) when muddy water containing sediment of grades A and B was used. Among the three ρ gradients, the k ratio was the highest when ρ = 0.6 g/L. The k ratio was 1.27 when sediment of grade A and ρ = 0.6 g/L was used. The k ratio was 2.01 when sediment of grade B and ρ = 0.6 g/L was used. The k ratio exhibited a different trend (an increasing trend) when sediment of grade C was used compared with those when sediments of grade A or grade B were used. Overall, after fertilization, the k ratio was the greatest when sediment of grade B was used, followed by the situations when sediments of grades C and A were used. The greater the value of ρ was, the smaller the effect of irrigation water temperature, indicating that irrigation water temperature had the largest impact on sediment of grade B and the smallest impact on sediment of grade A, which was consistent with the situation in which no fertilizer was applied.

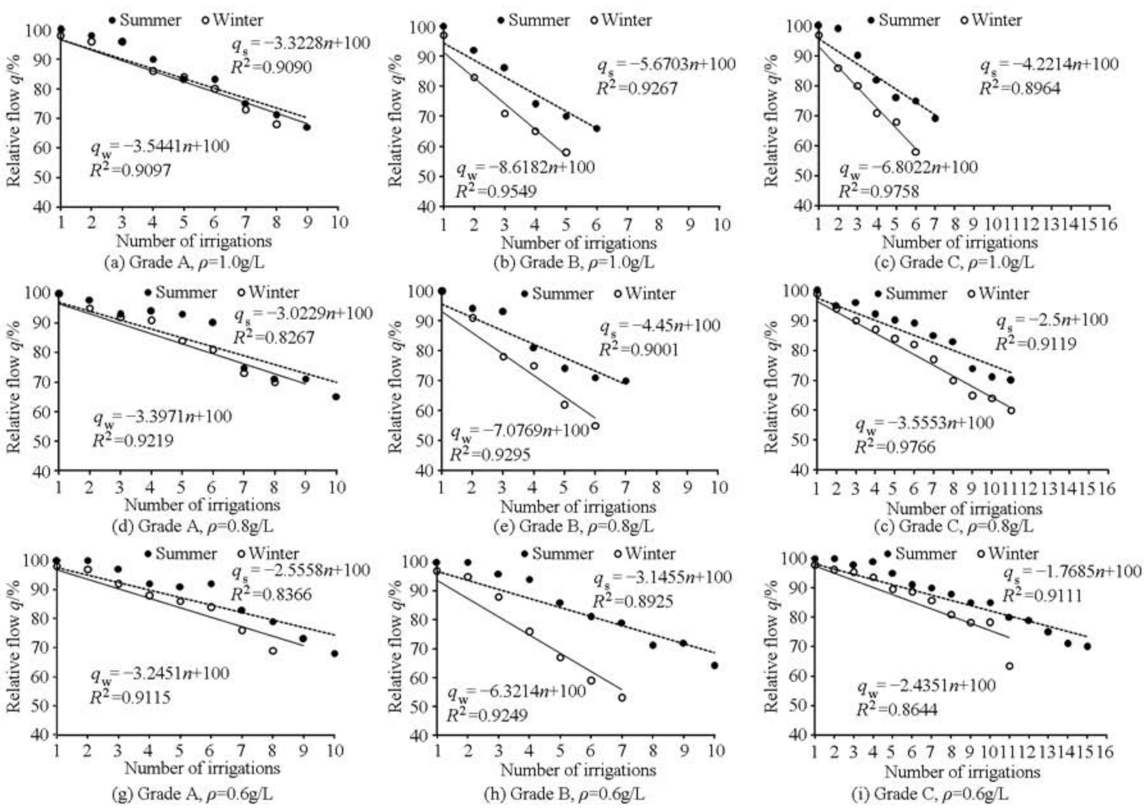

Fig. 2 Effect of irrigation water temperature, fertilizer concentration and sediment grade on relative flow

A comparison of Fig. 1 and Fig. 2 showed that fertigation increased the rate at which q was decreased with the increase of n and decreased the number of effective irrigations. In addition, the absolute value of k exhibited an increasing trend with increasing ρ. Furthermore, the emitter was clogged more rapidly, and fertilization significantly accelerated emitter clogging. After fertilization, the total number of effective irrigations in summer was 1.43 times of that in winter and was higher than the number of effective irrigations when no fertilizer was applied. However, irrigation with water at high temperature in summer did not change the effect of ρ on the acceleration of clogging and the size range of sediment particles that could easily cause clogging.

When ρ = 1.0 g/L, the absolute values of k were the largest when sediment of grade B was used (8.618 2 in winter and 5.670 3 in summer) and were the smallest when sediment of grade C was used (6.802 2 in winter and 4.221 4 in summer). Analysis of determination coefficients R^2 of the $q-n$ curves showed that fertilization reduced the number and extent of the oscillation changes of q. In addition, when the fertilizer was applied in winter, the R^2 was somewhat larger than that when no fertilizer was applied, whereas R^2 when the fertilizer was applied in summer was slightly smaller than that when no fertilizer was applied, indicating that fertilization reduced the probability of scouring the clogging that occurred in the previous irrigation period. When the irrigation water temperature was higher in summer, the scouring effect of the irrigation water was somewhat increased, and the number of effective irrigations was also increased.

The relationship between ρ and the absolute value of k was fitted using an exponential function $|k| = ae^{m\rho}$ (Fig. 3), where the coefficient a reflects the characteristics of the sediment grade (sediment grade can cause emitter clogging more easily with higher value of a), and m reflects the sensitivity of the effect of ρ on clogging (the effect of ρ on emitter clogging was more sensitive with greater value of m).

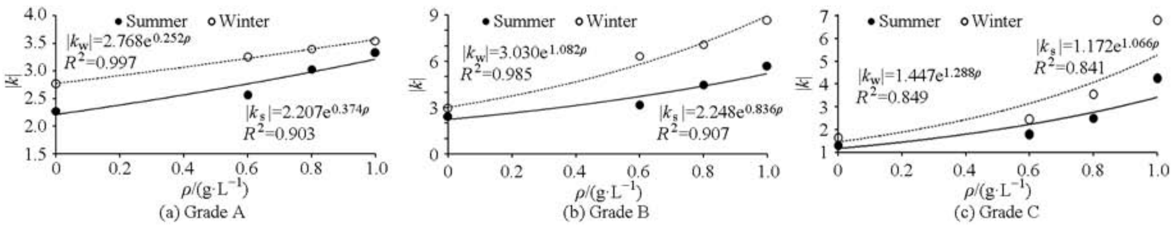

Fig. 3 Relationship of ρ and absolute value of curve slope k of relative flow and irrigation numbers

Fig. 3 showed that the coefficient a was the highest in both winter and summer when sediment of grade B was used; thus, sediment of grade B easily caused clogging. The sensitivity coefficient m was the greatest when sediment of grade C was used, and the sensitivity of the effect of ρ on clogging was the greatest when sediment of grade C was used. These observations indicated that at high contents of particles of size 0.067 ~ 0.1 mm, the sensitivity of the effect of ρ on clogging was great. When sediment of grades B or C (particle sizes of mainly 0.034 ~ 0.1 mm) was used, the sensitivity of the effect of ρ on clogging was higher in winter than that in summer. When sediment of grade A was used, the sensitivity of the effect of ρ on clogging was lower in winter than that in summer.

3 Discussion

Irrigation water temperature affects the anti-clogging performance of emitter mainly by affecting the internal energy, viscosity coefficient and diffusion coefficient of the fluid, as well as affecting the physical and chemical actions of the solute and microbial communities. In addition, even when no clogging occurs, decrease in temperature can slightly decrease the outflow of emitter, thus increasing the probability of emitter clogging[20]. Therefore, statistically, significant antagonistic action occurs among sediment grade, ρ, and irrigation water temperature with the experiment conducted in the present study as the research background.

In terms of the effect of irrigation water temperature and sediment grade on emitter clogging, increase of irrigation water temperature increased the thickness of the electrical double layers between sediment particles in the irrigation water, increased the repulsion between the sediment particles, and decreased the shear force between the sediment particles[14,21-22]. In addition, increase of irrigation water temperature increased the internal energy of water, decreased the viscosity coefficient of water, and weakened the hydrogen bonds between water molecules. Consequently, the flocculation among sediment particles was weakened[13,23]. The aforementioned effects all promoted the anti-clogging performance of emitters. Furthermore, increased irrigation water temperature increased the flow of emitter and increased the capacity of water flow to carry sediment particles, thereby allowing sediment particles to flow more easily out of the channel with water flow[24]. Consequently, the probability of emitter clogging was reduced. The results also showed that the anti-clogging performance of the emitters was superior when drip irrigation was carried out in summer at high temperature compared with that in winter. The total number of effective irrigations in summer was approximately 1.26 times of that in winter. From the perspective of the anti-clogging performance of emitters, the number of irrigations should be reduced when irrigation water temperature was low.

Fertilization can change the concentration of cations in water. The majority of fine sediment particles carried negative charge. Cations compressed the electric double layer structure on the surface of sediment particles through neutralization[17], thereby reducing the static repulsion among sediment particles, affecting the flocculation among sediment particles, and thus affecting emitter clogging. After fertilization, the flocculation among sediment particles was increased. As a result, stable agglomerations can be formed more easily, which would clog the emitters. Increase of temperature increased the kinetic energy of water and sediment particles, decreased the shear force between sediment particles, and destroyed the agglomerations to a certain extent[25]. Consequently, increase of scouring was occurred. In the present study, the content of large particles (0.067 ~ 0.1 mm) was high in sediments of grade C. Flocculation among particles with sizes in this range was relatively weak. Therefore, the accumulation of sediment particles in the channels due to gravity was the main cause of clogging[26]. Li et al. studied the effect of fertilization with muddy water on emitter clogging and found that it was most difficult for sediments with contents of particle sizes in the range of 0.067 ~ 0.1 mm of greater than 50% to cause clogging; partial clogging was the main form of clogging when clogging did occur when these sediment grades were used[27]. Increase of temperature increased the kinetic energy of particles and decreased the settling velocity and degree of siltation of the particles[14]. Therefore, the aforementioned sediment grade was the most sensitive to the effect of temperature. Niu et al.[11] studied fine particles with sizes in the range of 0 ~ 0.1 mm without any added fertilizer and noted that increase of temperature can enhance the anti-clogging performance of emitters. Hills et al. investigated the effect of temperature variations (during the day, at night, and underground) on chemical clogging and found that increase in temperature promoted the rate at which precipitates such as calcium carbonate and magnesium carbonate were formed, thereby exacerbating the clogging[6]. In the present study, the content of calcium and magnesium ions in the irrigation water was far less than that in the aforementioned studies, and the temperature difference was greater. In addition, the sediment content was relatively high in the present study. The main cause of clogging was the deposition of sediment particles. When the irrigation water temperature was high, the solubility of the chemical fertilizer was increased, and crystallization as well as precipitation of the chemical fertilizer were decreased. Consequently, the anti-clogging performance of the emitters during the drip irrigation process using the fertigation technology was increased. The total number of effective irrigations in summer was 1.43 times of that in winter. Furthermore, because the microbial content was high in reclaimed water, when reclaimed water was used for irrigation, temperature would affect the development of the microorganisms and biofilms in the irrigation water; the formation and development of biofilms would promote bonding and flocculation among solid particles, thereby affecting emitter clogging.

It was found that for different sediment grades and fertilizer concentrations, the sensitivity of the effect of irrigation water temperature on clogging was different. Irrigation water temperature did not change the size range of particles that easily clogged emitters with specific structure, and it also did not change the trend of the effect of ρ on emitter clogging. A complex coupling effect between temperature and water quality was observed. Irrigation water temperature affected emitter clogging by affecting the physical, chemical and biological characteristics of the solution and solutes in the water. Therefore, temperature had long-term effect on physical, chemical and biological clogging. Further in-depth research would be necessary to classify water quality and the critical temperatures for different types of clogging.

4 Conclusions

(1) Due to differences in the irrigation season, irrigation water temperature was an important factor that affected the anti-clogging performance of the emitters. The anti-clogging performance of the emitters when irrigation was carried out in summer was superior to that when irrigation was carried out in winter.

(2) Fertilization accelerated the clogging effect of the emitters that was affected by irrigation water temperature. In addition, the effect of irrigation water

temperature on clogging was less significant with higher value of ρ.

(3) For muddy water, when the particle content lay in the size range of 0.034 ~ 0.1 mm was greater than 50%, the sensitivity of the effect of ρ on clogging was higher in winter than in summer. ρ should be more strictly controlled during winter irrigation.

(4) The effect of irrigation water temperature on emitter clogging was far less significant than those of sediment concentration and ρ. Variations of irrigation water temperature within a certain range did not change the overall trend of the effect of sediment concentration and ρ on emitter clogging.

References

[1] Nakayama F S, Bucks D A. Water quality in drip trickle irrigation: a review[J]. Irrigation Science, 1991, 12(1): 187 – 192.

[2] Ge Lingxing, Wei Zhengying, Cao Meng, et al. Deposition law of sand in labyrinth-channel of emitter [J]. Transactions of the CSAE, 2010, 26(3): 20 – 24. (in Chinese)

[3] Liu Lu, Niu Wenquan, Zhou Bob. Influence of sediment particle size on clogging performance of labyrinth path emitters[J]. Transactions of the CSAE, 2012, 28(1): 87 – 93. (in Chinese)

[4] Li Zhiqin, Chen Gang, Yang Xiaochi. Experimental study of physical clogging factor of labyrinth emitter caused by muddy water [J]. Journal of Xi'an University of Technology, 2006, 22(4): 395 – 398. (in Chinese)

[5] Wang Yalin, Zhu Delan, Zhang Lin, et al. Experimental study on sediment distribution in lateral pipes and clogging of emitter [J]. Transactions of the Chinese Society for Agricultural Machinery, 2014, 45(6): 177 – 182.

[6] Hills D J, Nawar F M, Waller P M. Effects of chemical clogging on drip-tape irrigation uniformity [J]. Transactions of the ASAE, 1989, 32(4): 1202 – 1206.

[7] Liu Yanfang, Wu Pute, Zhu Delan, et al. Clogging of labyrinth emitters in greenhouse fertigation [J]. Transactions of the Chinese Society for Agricultural Machinery, 2014, 45(12): 50 – 55. (in Chinese)

[8] Xu Wenli, Li Zhiqin. Experimental study on clogging and the capability of sediment transportation about labyrinth emitter[J]. Shanxi Hydrotechnics, 2008(2): 10 – 12. (in Chinese)

[9] Liu Huajun, Huang Guanhua, Wang Pengchao, et al. Effect of drip irrigation with reclaimed water on emitter clogging[J]. Transactions of the CSAE, 2009, 25(9): 15 – 20. (in Chinese)

[10] Li Yunkai, Wang Weinan, Sun Haosu. Particle-wall collision characteristics influenced by biofilms in drip irrigation laterals with reclaimed water[J]. Transactions of the Chinese Society for Agricultural Machinery, 2015, 46(9): 159 – 166. (in Chinese)

[11] Niu Wenquan, Liu Lu. Influences of sediment concentration and water temperature of muddy water on emitter clogging[J]. Transactions of the Chinese Society for Agricultural Machinery, 2012, 43(3): 39 – 45. (in Chinese)

[12] Zhou Bo, Li Yunkai, Liu Yaoze, et al. Effects of flow path depth on emitter clogging and surface topographical characteristics of biofilms[J]. Irrigation and Drainage, 2014, 63(1): 46 – 58.

[13] Lou Yanmin, Liu Juanhong, Zhou Xiaoping, et al. Temperature on the viscosity and diffusion coefficient of water [J]. Journal of Southwest China Normal University: Natural Science Edition, 2009, 34(6): 34 – 39. (in Chinese)

[14] Lau Y L. Influence of temperature on deposition rate and deposition of cohesive sediment[J]. Express Water Resources & Hydropower Information, 1994(13): 21 – 24. (in Chinese)

[15] Pitts D J, Haman D Z, Smajstria A G. Causes and prevention of emitter plugging in microirrigation systems [J]. University of Florida IFAS Extension, BUL 258, 1990: 1 – 11.

[16] Bozkurt S, Ozekici B. The Effect of fertigation management in the different type of in-line emitters on trickle irrigation system performance [J]. Journal of Applied Science, 2006, 6(5): 1165 – 1171.

[17] Wang Jiasheng, Chen Li, Liu Lin, et al. Experimental study of the effect of cation concentration on sediment settling velocity[J]. Advances in Water Asience, 2005, 16(2): 169 – 173. (in Chinese)

[18] ISO/TC 23/SC 18/WG5 N12 Clogging test methods for emitters[S]. 2006.

[19] SL 103—95 Standard of micro-irrigation engineering and technical [S]. 1995.

[20] Peng G F, Wu I P, Phene C J. Temperature effects on drip line hydraulics [J]. Transactions of the ASAE, 1986, 9(1): 211 – 215.

[21] Duffadar R, Klasin S, Davis J M, et al. The impact of nanoscale chemical features on micro-scale adhesion crossover from heterogeneity-dominated to mean-field behavior[J]. Journal of Colloid and Interface Science, 2009, 337(2): 396 – 407.

[22] Hong Guojun, Yang Tiesheng. 3-D simulation of flocculation-settling of cohesive fine sediment [J]. Journal of Hydraulic Engineering, 2006, 37(2): 172 –

177. (in Chinese)

[23] Zhou Jian, Lu Xiaohua, Wang Yanru, et al. Molecular dynamics simulation of water at different temperatures [J]. Computers and Applied Chemsitry, 1999, 16(4): 241 - 244. (in Chinese)

[24] Xu Mingjin, Nie Jing, Ge Xufeng, et al. Experiment of hydraulic trait of drip irrigation strap under low pressure and the influence of temperature on emitter discharge [J]. China Rural Water and Hydropower, 2010(12): 8 - 10. (in Chinese)

[25] Liu Lin, Chen Li, Wang Jiasheng, et al. Effect on the flocculation sedimentation velocity in different conditions of cation concentration by concentration of sediments particles[J]. Engineering Journal of Wuhan University, 2007, 40(1): 29 - 32. (in Chinese)

[26] Zhang Deru, Liang Zhiyong. Experiment study of effect of nonuniform fine sediment on flocculation[J]. Hydro-Science and Engineering, 1994(Supp. 1): 11 - 17. (in Chinese)

[27] Li Kangyong, Niu Wenquan, Zhang Ruochan, et al. Accelerative effect of fertigation on emitter clogging by muddy water irrigation[J]. Transactions of the CSAE, 2015, 31(17): 81 - 90. (in Chinese)

doi:10.6041/j.issn.1000-1298.2016.02.014

温度对施肥滴灌系统滴头堵塞的影响

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摘要: 为探究不同灌水温度下水肥一体化滴灌滴头堵塞成因与过程,采用固定周期间歇滴灌的多因素完全随机试验设计方法,分别在冬、夏两个季节研究了3种不同泥沙级配浑水与3个不同施肥质量浓度组合对滴头堵塞的影响和堵塞变化过程。结果表明,灌水温度是影响滴头堵塞的重要因素,与水质交互耦合效应显著,夏季施肥和未施肥2种情况下灌溉滴头的抗堵塞性能均高于冬季,夏季有效灌水次数是冬季的1.26~1.43倍;施肥加速滴头堵塞的作用受泥沙级配和灌水温度的影响,冬季灌溉水中0.034~0.1 mm粒径粗颗粒含量越多,施肥质量浓度对堵塞的影响越敏感,夏季灌溉水中0~0.034 mm细颗粒越多,施肥质量浓度对堵塞的影响越敏感。建议灌水温度较低时,水肥一体化滴灌应控制在较低的施肥质量浓度下灌溉,适当增大次灌水时间,减少灌溉次数。

关键词: 滴头; 堵塞; 温度; 施肥质量浓度; 泥沙级配
中图分类号: S275.6 **文献标识码:** A **文章编号:** 1000-1298(2016)02-0098-07

Influence of Temperature on Emitter Clogging with Fertigation through Drip Irrigation System

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Abstract: Fertilizers injected into the drip irrigation system may contribute to serious clogging, which occurs due to multiple factors, including water quality, water condition, hydraulic parameters and system design. To better understand the causes and process of emitter clogging of fertigation at different irrigation water temperature levels, laboratory experiments were conducted to investigate the effects of irrigation water temperature on the sensitivity of emitter clogging. Three different particle gradations and three different fertilizer concentrations were investigated through the intermittent drip irrigation method in summer and winter, respectively. Experiment results showed that the temperature of irrigation water was an important factor causing clogging with remarkable coupling effect with water quality. The anti-clogging performance of emitter in summer was always better than that in winter for both scenarios of fertilization and no fertilization. The acceleration of drip clogging with fertilization was affected by the sediment gradation and the season. When the content of sediment particles (with diameter of 0.034 ~ 0.1 mm) became high, the fertilizer concentration could be more sensitive to clogging in winter than that in summer. The fertilizer concentration became more sensitive to clogging when the content of sediment particles (with diameter of 0 ~ 0.034 mm) were high in summer than that in winter. The number of effective irrigation frequency in summer was 1.26 ~ 1.43 times as much as it was in winter. However, the irrigation water temperature could not change its effect on clogging caused by sediment gradation and fertilization concentration. Therefore, it is recommended that the irrigation frequency can be reduced

收稿日期: 2015-09-16 修回日期: 2015-11-29
基金项目: "十二五"国家科技支撑计划项目(2015BAD24B01)和国家自然科学基金项目(51379024)
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when the temperature stays low, and the fertilizer concentration can be controlled at a low level when irrigation is applied with fertilizer.

Key words: emitter; clogging; temperature; fertilizer mass concentration; sediment gradation

引言

滴头堵塞问题是影响滴灌系统灌水质量及系统使用寿命的重要因素之一，也是滴灌技术领域的研究热点之一。根据堵塞成因，滴头堵塞分为物理、化学和生物堵塞 3 类[1]，但实际堵塞往往是上述 3 种因素相互作用的结果。经过滤灌溉水中仍有细小泥沙[2]进入迷宫流道，引起滴头逐渐封堵，研究[3-5]表明，不同结构的滴头可能存在不同易堵塞的敏感泥沙粒径范围和级配，实际灌溉水中可以通过采取对特定粒径段泥沙颗粒过滤或者沉淀等方法控制滴头堵塞发生。另外，灌溉水中总是存在一定量的化学可溶性物质与微生物菌群，其中钙、镁和磷等离子的置换、结晶和沉淀等理化过程也会促进滴头堵塞，一般认为灌溉水的碱性越强，引起滴头化学堵塞的几率越大[6-8]。灌溉水中微生物的繁殖、生物膜的形成会加强物理性及化学性颗粒间的粘结沉积，也是诱发滴头堵塞的重要因素[9-10]。除上述 3 种水质因素外，滴头堵塞还受其自身的水力参数及滴灌系统运行管理水平等因素的影响[11-12]，其中灌水温度不连贯对滴头堵塞影响的研究极少涉及。

由于灌溉季节不同，灌溉区域不同，灌溉水的温度差异较大，研究灌溉水温度对滴头堵塞的影响，对于制定不同区域、不同季节的灌溉管理策略具有重要意义。一般认为温度升高会增加颗粒碰撞概率，促进絮凝形成，也可促使化学沉淀增加，在一定程度上加剧滴头的堵塞。但温度升高的同时既增加了泥沙颗粒双电层厚度，降低水的粘滞系数，又抑制微生物的生长，减少了生物成膜的捕捉效应，结果反而增强了滴头的抗堵塞性能[6, 13-14]。牛文全等[11]研究了灌溉水温和粒径小于 0.1 mm 泥沙颗粒对滴头堵塞的影响，认为温度升高增加滴头的抗堵塞性能；Hills 等研究了温度对化学堵塞的影响，发现温度升高增加了碳酸钙和碳酸镁等的沉淀，加剧了滴头堵塞[6]。但由于准确控制灌溉水的温度相对较难，目前就温度对灌水水质类型及流道结构等因素引起堵塞的影响还没有明确的结论。另外，随着水肥一体化技术的快速发展，水肥一体化滴灌引起的堵塞问题越来越引起广泛的关注[15-16]，施肥带入的阳离子会影响颗粒间的絮凝作用[17]，灌溉水的温度如何影响颗粒间的絮凝作用以及温度、泥沙、施肥 3 因素共同作用下如何影响滴头堵塞机理还有待进一步研究。

因此，本文以迷宫流道内镶片式滴头为试验滴头，分别在夏季与冬季水温相差较大的条件下，通过配置不同泥沙级配及施肥浓度组合的水质类型，进行固定周期的间歇式浑水灌溉试验，分析灌水温度对水肥一体化灌溉技术滴头抗堵塞性的影响，为制定合理的水肥灌溉管理策略提供依据。

1　试验材料与方法

1.1　试验材料与装置

试验用滴灌带为内镶片式齿形迷宫流道滴灌带（杨凌秦川节水灌溉设备工程有限公司），工作压力为 40 kPa 时，滴头额定流量 q = 2.3 L/h，管径为 16 mm，壁厚 0.2 mm。滴头进水口栅格数为 8，流道宽 0.8 mm，齿高 1.1 mm，齿间距为 3 mm，流道单元数 14 个，滴头的制造偏差为 1.76%。试验用水为杨凌地下水，pH 值为 7.54，细菌总数为零，硬度为 340 mg/L，悬浮颗粒数为零，电导率为 650 μS/cm。试验化肥为复合肥（陕西景盛肥业集团有限公司），主要成分为磷酸一胺、磷酸二胺、硫酸铵、硫酸钾和尿素，N、P、K 3 种养分含量质量比为 1∶1∶1。为确保肥料完全水溶，首先将复合肥溶解于玻璃烧杯中，经玻璃棒充分搅拌，静置 1 h 后观察肥料包膜材料是否发生沉降或悬浮等情况，最后取上层透明液体加入测试系统。试验泥沙是经水筛洗后的杨凌砂壤土，为消除泥沙表面吸附的盐离子对试验的干扰，先用清水冲洗泥沙过 0.1 mm 筛网，收集过筛浑水，沉淀去除上层清液。先后分别用 0.067 mm 与 0.034 mm 筛网对沉积泥沙反复淋洗，收集残留在筛网里的泥沙。对粒径小于 0.034 mm 泥沙进行沉淀去除上层清液，加水稀释后再重复此操作，最后收集沉积泥沙。

抗堵塞测试平台参照 GB/T 17187—2009、SL/T 67.2—1994 以及国际抗堵塞研究标准草案[18]关于室内灌水器堵塞敏感性试验搭建而成，试验装置由压力变频设备、数据自动采集设备、水沙混合设备和堵塞测试台组成。变频调压表由计算机控制，控制精度为 0.01 m 水头；数据采集装置由计算机控制电子秤实现即时测量，设定数据自动采集时间间隔为 1 s，数据采集误差为 0.2 g；水沙混合设备由水箱、潜水泵和搅拌机组成，通过搅拌机搅拌使浑水混合均匀。测试平台共 4 条毛管，相邻毛管间距为 30 cm，

每条毛管有5个滴头，相邻滴头间距为45 cm，共20个滴头。

1.2 试验方法

试验分2个阶段进行，分别在冬季（2014-12-01—2015-01-10）和夏季（2015-06-03—2015-07-05）进行，每次测试前，先用温度计测量灌溉水的温度，冬季阶段最低水温为3℃，最高水温为8℃，平均为5℃，夏季阶段最低水温为19℃，最高水温为29℃，平均为23℃。

设置3个泥沙级配，编号为A、B、C，含沙量（泥沙质量浓度）均为1 g/L（表1）；为加速堵塞效果，设置3个施肥质量浓度ρ：1.0、0.8、0.6 g/L，不施肥作为对照（ρ为零）；2个灌水季节：冬季灌水和夏季灌水；共24个处理，每个处理进行2次试验重复，每次铺设4条毛管，每个毛管有5个滴头，每2条毛管作为1个重复，共4次重复，每次灌水结束后，记录滴头平均流量。

表1 试验泥沙级配（质量分数）

Tab.1 Sediment particle size distribution %

泥沙级配编号	不同粒径颗粒所占百分比		
	0~0.034 mm	0.034~0.067 mm	0.067~0.1 mm
A	56.12	24.16	19.72
B	14.21	58.34	27.45
C	20.27	19.47	60.26

采用固定周期的间歇浑水抗堵塞试验方法，测试压力为40 kPa，每次灌水30 min，灌水间隔4 h，灌水结束后通过称量传感器记录每个滴头的流量，计算每根毛管的浑水平均流量与清水流量之比，即平均相对流量q。当$q<70\%$时，停止灌水并记录灌水次数以及完全堵塞滴头的个数。

1.3 评价指标与方法

我国《微灌工程技术规范》认为当滴头流量小于设计流量的75%时滴头已经发生严重堵塞[19]；国际微灌系统关于灌水器堵塞测试标准草案对滴灌堵塞的定义为：当滴头流量降幅达到25%～30%则认为发生严重堵塞[19]。为了放大试验结果，适当延长灌水次数，故本试验采用相对流量q小于初始流量的70%作为评价系统堵塞的判据。当$q<70\%$时，认为灌水系统整体发生了严重堵塞，停止灌水，记录灌水次数。平均相对流量q计算公式为

$$q=\left(\sum_{i=1}^{N}\frac{q_i}{q_{pi}}\right)\Big/N \qquad (1)$$

式中 q——平均相对流量，%

i——滴头序号 N——滴头总数

q_i——第i个滴头的浑水流量，L/h

q_{pi}——第i个滴头的清水流量，L/h

随着灌水次数的增加，流道冲淤总是往复进行，q变化呈波动下降趋势，对于$q\geqslant70\%$的灌水过程称为有效灌水（有效灌水次数），将发生堵塞滴头数与总滴头数之比称为堵塞率。

2 结果与分析

2.1 试验参数对堵塞的影响程度

由于灌水温度可控性低，本研究设计灌水温度控制在两个范围内（3～8℃和19～29℃）。为探讨区段内温度的变化是否对堵塞发生有影响，首先采用SPSS 22.0软件对灌水温度做单因素方差分析，结果显示温度段群组之间有显著差异（$P=0.021<0.05$），温度段群组之内差异不显著，说明可忽略区段内温度变化对堵塞的影响。然后进一步探明各参数对滴头堵塞的影响程度，对滴头流量进行单因变量多因素方差分析，选用Duncan多重比较模型。从方差分析的结果可以看出（表2），在95%的置信度条件下，施肥质量浓度、泥沙级配以及灌水温度3个因素的P值均小于0.05，说明三者对滴头相对流量的影响均达到极显著水平，是滴头堵塞发生的重要影响因素。而施肥质量浓度、泥沙级配与灌水温度之间的交互作用均未达到显著水平（$P>0.05$），该统计结果从另一侧面说明了温度区段内各因素的交互作用对堵塞的影响并不明显，表明温度对施肥质量浓度以及泥沙级配两因素对滴头堵塞的影响有复杂的拮抗作用。

表2 试验结果方差分析

Tab.2 Analysis of variance for total test data

方差来源	平方和	自由度	均方	F
泥沙级配	2.777	2	1.388	16.026**
灌水温度	0.770	1	0.770	8.887**
施肥质量浓度	2.208	3	0.736	8.495**
泥沙级配×温度	0.010	2	0.005	0.059ns
施肥质量浓度×级配	1.436	6	0.239	2.763*
施肥质量浓度×温度	0.109	3	0.036	0.418ns
施肥质量浓度×级配×温度	0.278	6	0.046	0.535ns
误差	6.237	72	0.087	

注：*、** 表示在$P<0.05$、$P<0.01$水平差异显著，ns表示差异不显著（$P>0.05$）。

2.2 温度与泥沙级配共同作用对滴头堵塞的影响

不同温度不施肥条件下，3种泥沙级配浑水试验滴头相对流量q随灌水次数的变化趋势如图1所示（下标w表示冬季，s表示夏季）。

为了便于分析，用线性关系近似拟合相对流量q随灌水次数n的变化过程，即

$$q=kn+b \qquad (2)$$

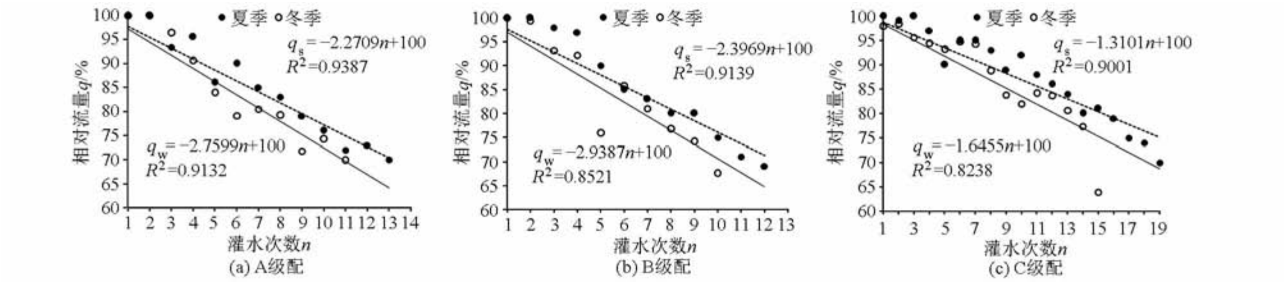

图 1　相对流量随灌水次数增加的变化趋势

Fig. 1　Variation tendency of relative flow with irrigation frequency

式中　k ——q 与 n 关系曲线的斜率

b ——在纵坐标轴上的截距

$q-n$ 曲线斜率 k 可表征不同泥沙级配浑水滴灌过程中，相对流量 q 随灌水次数 n 的下降速度，k 绝对值越大，堵塞发展越快。

由图 1 可知，冬季相对流量 q_w 基本小于夏季 q_s，冬季相对流量随灌水次数 n 增加的下降趋势也大于夏季。B 级配 k 绝对值最大，C 级配 k 绝对值最小，说明 B 级配最易发生堵塞，C 级配相对难发生堵塞；同种级配条件下不同温度 2 条相对流量变化曲线之间的开口程度为两者曲线方程 k 值之比，夏季相对流量 q 下降趋势相对冬季较为平缓，冬季 k 为夏季的 1.21～1.26 倍，C 级配冬季和夏季 k 的比值相对最高，说明灌溉水中 0.067～0.1 mm 粒径粗颗粒含量越多，温度对滴头堵塞的影响越大。另外，分析决定系数 R^2 可以发现，随着 0.067～0.1 mm 粒径泥沙颗粒的增加，冬季和夏季的 R^2 均呈减小趋势，冬季 R^2 总体小于夏季。说明灌溉水中 0.067～0.1 mm 粒径段泥沙颗粒越多，滴头相邻灌水周期冲淤越明显，堵塞-清洗的振荡现象频繁，堵塞发生阶段的随机性较为强烈。同理，冬季浑水滴灌较夏季而言，堵塞-清洗的振荡现象略为明显，即夏季流量变化相对比较平稳。

从图 1 还可以看出，夏季比冬季提高了有效灌水次数，k 绝对值越小，有效灌水次数的增加越多，易发生堵塞的 B 级配增加了 2 次，而难堵塞的 C 级配增加了 5 次，夏季总有效灌水次数约为冬季的 1.26 倍，说明较高水温的滴灌可显著提高有效灌水次数。但灌溉水温度没有改变易堵塞泥沙粒径范围，冬季和夏季均为 B 级配易堵塞，C 级配最不易堵塞。

2.3　温度与施肥浓度共同作用对滴头堵塞的影响

不同施肥浓度下，浑水滴灌滴头相对流量 q 随灌水次数 n 的变化趋势如图 2 所示。从图 2 可知，A、B 级配浑水随施肥质量浓度的增加（从 0.6 g/L 增加到 1.0 g/L），夏季和冬季 k 的比值呈减小趋势，3 个施肥质量浓度梯度中，施肥质量浓度为 0.6 g/L 的夏季和冬季 k 比值最大，A、B 级配分别为 1.27 和 2.01，C 级配则不同，呈增加趋势。总体而言，施肥后，夏季和冬季 k 比值由大到小依次为：B 级配、C 级配、A 级配，施肥质量浓度越大，温度的影响越小，说明灌溉水温度对 B 级配影响最大，对 A 级配影响最小，这与未施肥情况基本相同。

对比图 1 和图 2 可以看出，水肥一体化灌溉增大了相对流量 q 随灌水次数增加的下降速度，减少了有效灌水次数，且随着施肥质量浓度增加 k 的绝对值呈增大趋势，滴头堵塞发展越来越快，施肥明显加速了滴头堵塞。施肥后夏季总有效灌水次数是冬季的 1.43 倍，高于未施肥的情况。但夏季较高水温灌溉没有改变施肥质量浓度加速堵塞的作用，也没有改变易堵塞颗粒粒径范围。施肥质量浓度为 1.0 g/L 时，B 级配 k 绝对值最大，冬季和夏季分别为 8.618 2 和 5.670 3，C 级配 k 绝对值最小，冬季和夏季分别为 6.802 2 和 4.221 4。分析 $q-n$ 曲线的决定系数发现，施肥减少了流量的振荡变化次数和幅度。冬季施肥的 R^2 较未施肥有所提高，而夏季 R^2 则略有下降。说明施肥降低了对上次灌水发生堵塞的冲洗机率，当夏季灌溉水温度较高时，灌水冲洗作用有所增强，增加了有效灌水次数。

采用指数函数 $|k|=ae^{m\rho}$ 拟合施肥质量浓度 ρ 和斜率 k 绝对值的关系（图 3）。系数 a 反映泥沙级配特性，a 越大，则该级配越易引起滴头堵塞。m 反映施肥质量浓度对堵塞影响的敏感性，m 越大，施肥质量浓度对滴头堵塞的影响越敏感。

从图 3 可以看出，B 级配冬季和夏季的系数 a 均最大，属于易堵塞级配，C 级配敏感系数 m 最大，施肥质量浓度对该级配堵塞影响的敏感性最高。说明 0.067～0.1 mm 粒径颗粒含量越多，施肥质量浓度对堵塞影响的敏感性越强。对于以 0.034～0.1 mm 粒径颗粒为主的 B、C 级配，冬季施肥质量浓度对堵塞影响的敏感性高于夏季，而 A 级配相反。

3　讨论

灌水温度对灌水器堵塞的影响，主要通过温度

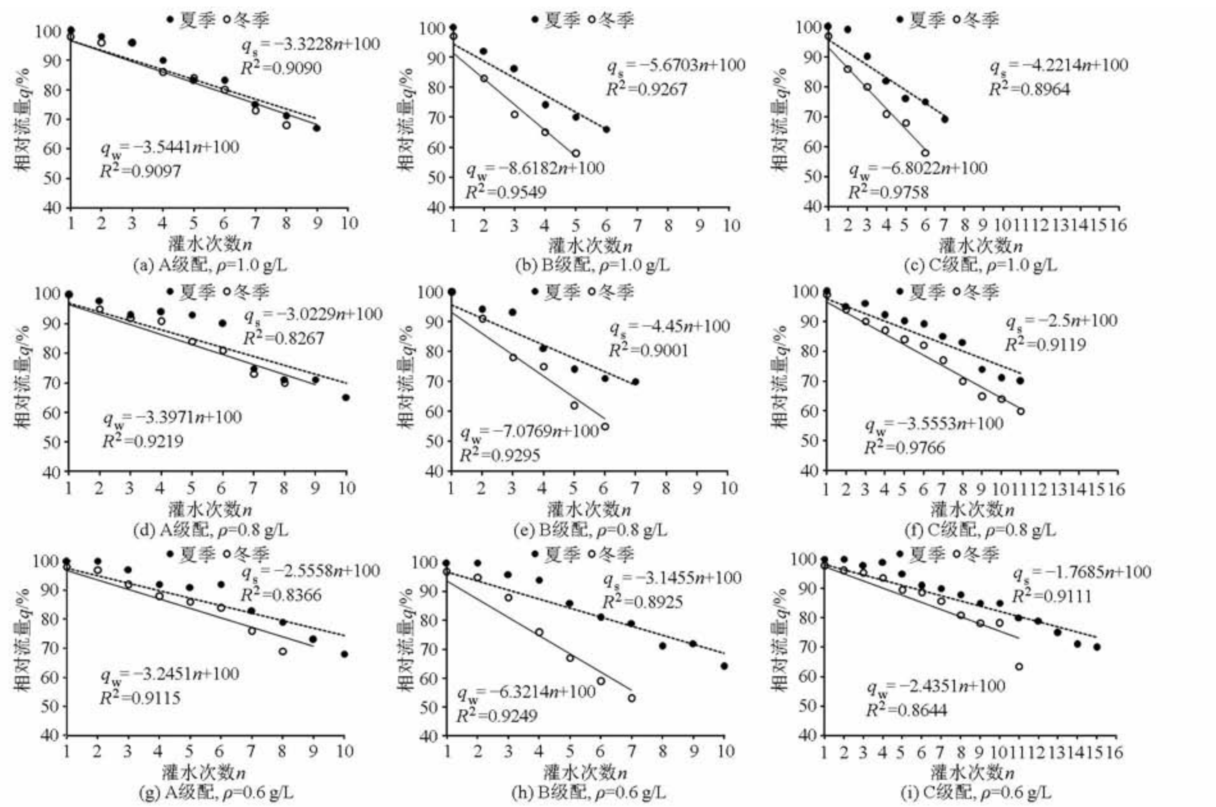

图2　温度、施肥浓度和泥沙级配对流量的影响

Fig. 2　Influence of irrigation water temperature, fertilizer concentration and sediment gradation on relative flow

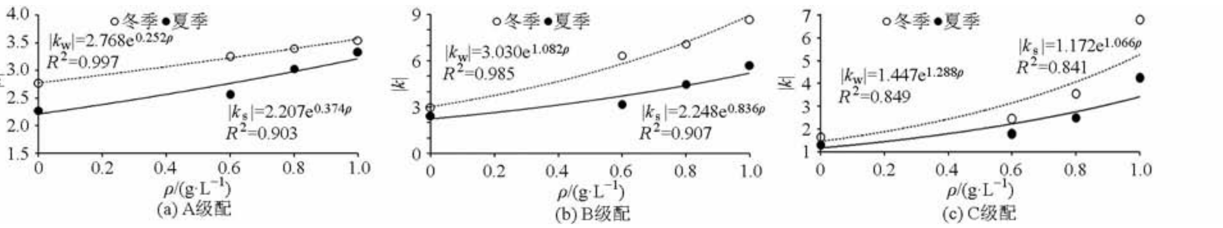

图3　施肥浓度 ρ 与斜率 $|k|$ 的关系

Fig. 3　Relation between fertilizer concentration ρ and absolute value of curve slop k of relative flow and irrigation frequency

影响流体的内能、粘度系数和扩散系数，以及溶质的物理、化学作用和微生物群落等途径影响滴头的抗堵塞性能。另外，即使在无堵塞发生的情况下，温度降低也可略微降低滴头出流量，进而增加滴头的堵塞发生机率[20]。因此，以本试验为研究背景的泥沙级配、施肥质量浓度以及灌水温度间存在统计学上明显的拮抗作用。

就温度与泥沙级配对滴头堵塞的影响来看，灌水温度的升高增加了灌溉水中泥沙颗粒间的双电层厚度，增大了颗粒间的排斥力，减小泥沙颗粒间的剪切力[14, 21-22]。同时，温度升高增加了水的内能，降低水的粘滞系数，减弱水分子间氢键力，颗粒间的絮凝作用减弱[13, 23]，这都有助于提高滴头的抗堵塞性能。另外，温度升高滴头流量有所增加，增加了水流的挟沙能力，使泥沙更易随水流流出流道[24]，减缓了滴头堵塞的发生。本试验也发现灌溉水温度较高的夏季滴灌，滴头抗堵塞能力优于冬季灌水，总有效灌水次数约为冬季的1.26倍，从滴头抗堵塞角度考虑，当温度较低时，应减少安排灌溉计划。

施肥会改变水中阳离子浓度，而大多数细颗粒泥沙带有负电荷，阳离子通过中和压缩泥沙表面的双电层结构[17]，减小了泥沙颗粒之间的静电斥力，影响泥沙的絮凝作用，从而对滴头堵塞产生影响。施肥后，泥沙絮凝作用增强，更容易形成稳定的团聚结构堵塞滴头。而当温度升高时，增大了水和泥沙颗粒的动能，减小颗粒间的剪切力，一定程度上破坏了团聚体[25]，出现了冲洗增强的现象。本试验C级配中0.067～0.1 mm较大粒径颗粒含量多，而此粒径段颗粒絮凝作用较弱，重力作用引起的流道堆积是造成堵塞的主要原因[26]。李康永等就浑水施肥对滴头堵塞的影响研究表明，粒径0.067～0.1 mm颗粒含量大于50%的级配最不易引起堵塞，且以部分堵塞为主[27]。当温度升高，颗粒动能增加，沉速和淤积度降低[14]，因此，该段级配受温度影响最敏

感。牛文全等[11]在未添加肥料情况下，对粒径为 0～0.1 mm 的细小泥沙研究发现温度升高会加强滴头的抗堵塞性能，Hills 等以白天、夜间地下等温差方式研究了温度变化对化学堵塞的影响，发现由于温度升高促进碳酸钙和碳酸镁等沉淀物的生成速率，从而加剧了堵塞[6]。而本试验灌溉水中钙、镁离子含量远小于前述试验，且试验温差大于前述试验，另外，本试验含沙量较大，堵塞主要以泥沙沉积堵塞为主，当灌溉水温度较高时，化学肥料溶解性增强，结晶析出减弱，增强了滴头水肥一体化浑水灌溉的抗堵塞性能，夏季总有效灌水次数是冬季的 1.43 倍。另外，当使用再生水灌溉时，水中微生物含量丰富，温度将影响灌溉水中微生物及其生物膜的发育，而生物膜的形成和发育会促进固体颗粒间的粘结及颗粒间絮凝作用，从而对滴头堵塞产生影响。

本试验研究发现，对于不同的泥沙级配和施肥质量浓度，灌溉水温度对堵塞影响的敏感性不同，温度无法改变特定结构滴头的易堵塞敏感粒径范围，也不能改变施肥质量浓度对滴头堵塞的影响趋势，温度与水质间存在复杂的耦合效应，灌水温度通过改变水体中溶液与溶质物理、化学以及生物特性，来影响滴头堵塞的发生。因此，温度对物理、化学及生物综合堵塞发生有长期影响作用，对水质分类以及不同堵塞类型临界温度细化还有待后续深入研究。

4　结论

（1）灌溉季节不同，灌溉水温度不同，温度是影响滴头堵塞的重要因素。夏季灌溉滴头的抗堵塞性能高于冬季。

（2）施肥加速滴头堵塞的作用受灌水温度的影响，且施肥质量浓度越大，温度的影响越小。

（3）对于 0.034～0.1 mm 粒径颗粒超过 50% 的浑水，冬季施肥质量浓度对堵塞影响的敏感性高于夏季，冬季灌溉更应该严格控制施肥浓度。

（4）灌溉水温度对滴头堵塞的影响小于泥沙级配浓度和施肥质量浓度，灌溉水温在一定的变化范围内并不能改变泥沙级配和施肥质量浓度对堵塞影响的总趋势。

参　考　文　献

1　Nakayama F S, Bucks D A. Water quality in drip trickle irrigation: a review[J]. Irrigation Science, 1991,12(1): 187－192.

2　葛令行，魏正英，曹蒙，等．微小迷宫流道中的沙粒沉积规律[J]．农业工程学报，2010,26(3):20－24.
Ge Lingxing, Wei Zhengying, Cao Meng, et al. Deposition law of sand in labyrinth-channel of emitter[J]. Transactions of the CSAE, 2010,26(3):20－24. (in Chinese)

3　刘璐，牛文全，Bob Zhou．细小泥沙粒径对迷宫流道灌水器堵塞的影响[J]．农业工程学报，2012,28(1):87－93.
Liu Lu, Niu Wenquan, Bob Zhou. Influence of sediment particle size on clogging performance of labyrinth path emitters[J]. Transactions of the CSAE, 2012,28(1):87－93. (in Chinese)

4　李治勤，陈刚，杨晓池．浑水引起迷宫灌水器物理堵塞因素实验研究[J]．西安理工大学学报，2006,22(4):395－398.
Li Zhiqin, Chen Gang, Yang Xiaochi. Experimental study of physical clogging factor of labyrinth emitter caused by muddy water [J]. Journal of Xi'an University of Technology, 2006,22(4):395－398. (in Chinese)

5　王亚林，朱德兰，张林，等．滴灌毛管泥沙分布与灌水器堵塞试验研究[J]．农业机械学报，2014,45(6): 177－182.
Wang Yalin, Zhu Delan, Zhang Lin, et al. Experimental study on sediment distribution in lateral pipes and clogging of emitter [J]. Transactions of the Chinese Society for Agricultural Machinery, 2014,45(6):177－182. (in Chinese)

6　Hills D J, Nawar F M, Waller P M. Effects of chemical clogging on drip-tape irrigation uniformity[J]. Transactions of the ASAE, 1989, 32(4):1202－1206.

7　刘艳芳，吴普特，朱德兰，等．温室水肥滴灌系统迷宫式灌水器堵塞试验研究[J]．农业机械学报，2014,45(12):50－55.
Liu Yanfang, Wu Pute, Zhu Delan, et al. Clogging of labyrinth emitters in greenhouse fertigation[J]. Transactions of the Chinese Society for Agricultural Machinery, 2014,45(12):50－55. (in Chinese)

8　徐文礼，李治勤．迷宫灌水器堵塞与输沙能力实验研究[J]．山西水利科技，2008(2):10－12.
Xu Wenli, Li Zhiqin. Experimental study on clogging and the capability of sediment transportation about labyrinth emitter[J]. Shanxi Hydrotechnics, 2008(2):10－12. (in Chinese)

9　刘海军，黄冠华，王鹏超，等．再生水滴灌对滴头堵塞的影响[J]．农业工程学报，2009,25(9):15－20.
Liu Haijun, Huang Guanhua, Wang Pengchao, et al. Effect of drip irrigation with reclaimed water on emitter clogging[J]. Transactions of the CSAE, 2009,25(9):15－20. (in Chinese)

10　李云开，王伟楠，孙昊苏．再生水滴灌毛管内颗粒-管壁碰撞特性研究[J]．农业机械学报，2015,46(9): 159－166.
Li Yunkai, Wang Weinan, Sun Haosu. Particle-wall collision characteristics influenced by biofilms in drip irrigation laterals with reclaimed water[J]. Transactions of the Chinese Society for Agricultural Machinery, 2015,46(9): 159－166. (in Chinese)

11　牛文全，刘璐．浑水特性与水温对滴头抗堵塞性能的影响[J]．农业机械学报，2012,43(3):39－45.
Niu Wenquan, Liu Lu. Influences of sediment concentration and water temperature of muddy water on emitter clogging[J]. Transactions of the Chinese Society for Agricultural Machinery, 2012,43(3): 39－45. (in Chinese)

12 Zhou Bo, Li Yunkai, Liu Yaoze, et al. Effects of flow path depth on emitter clogging and surface topographical characteristics of biofilms[J]. Irrigation and Drainage, 2014, 63(1):46 – 58.
13 娄彦敏, 刘娟红, 周晓平, 等. 温度对水的粘度和扩散系数影响的研究[J]. 西南师范大学学报:自然科学版, 2009, 34(6): 34 – 39.
Lou Yanmin, Liu Juanhong, Zhou Xiaoping, et al. Temperature on the viscosity and diffusion coefficient of water[J]. Journal of Southwest China Normal University: Natural Science Edition, 2009, 34(6):34 – 39. (in Chinese)
14 Lau Y L. 温度对粘性泥沙的沉速及淤积的影响[J]. 水利水电快报, 1994(13): 21 – 24.
Lau Y L. Influence of temperature on deposition rate and deposition of cohesive sediment[J]. Express Water Resources & Hydropower Information, 1994(13): 21 – 24. (in Chinese)
15 Pitts D J, Haman D Z, Smajstria A G. Causes and prevention of emitter plugging in microirrigation systems[J]. University of Florida IFAS Extension, BUL 258,1990:1 – 11.
16 Bozkurt S, Ozekici B. The effect of fertigation management in the different type of in-line emitters on trickle irrigation system performance [J]. Journal of Applied Science, 2006, 6(5):1165 – 1171.
17 王家生, 陈立, 刘林, 等. 阳离子浓度对泥沙沉速影响实验研究[J]. 水科学进展, 2005,16(2):169 – 173.
Wang Jiasheng, Chen Li, Liu Lin, et al. Experimental study of the effect of cation concentration on sediment settling velocity[J]. Advances in Water Asience, 2005, 16(2): 169 – 173. (in Chinese)
18 ISO/TC 23/SC 18/WG5 N12 Clogging test methods for emitters[S]. 2006.
19 SL 103—95 微灌工程技术规范[S]. 1995.
20 Peng G F, Wu I P, Phene C J. Temperature effects on drip line hydraulics[J]. Transactions of the ASAE, 1986, 9(1): 211 –215.
21 Duffadar R, Klasin S, Davis J M, et al. The impact of nanoscale chemical features on micron-scale adhesion crossover from heterogeneity-dominated to mean-field behavior[J]. Journal of Colloid and Interface Science, 2009, 337(2): 396 – 407.
22 洪国军, 杨铁笙. 黏性细颗粒泥沙絮凝及沉降的三维模拟[J]. 水利学报, 2006, 37(2): 172 – 177.
Hong Guojun, Yang Tiesheng. 3-D simulation of flocculation-settling of cohesive fine sediment[J]. Journal of Hydraulic Engineering, 2006, 37(2): 172 – 177. (in Chinese)
23 周健, 陆小华, 王延儒, 等. 不同温度下水的分子动力学模拟[J]. 计算机与应用化学, 1999, 16(4): 241 –244.
Zhou Jian, Lu Xiaohua, Wang Yanru, et al. Molecular dynamics simulation of water at different temperatures[J]. Computers and Applied Chemsitry, 1999, 16(4): 241 –244. (in Chinese)
24 徐明金, 聂境, 葛旭峰, 等. 低压条件下滴灌带的水力特性及温度影响效应试验[J]. 中国农村水利水电, 2010(12):8 – 10.
Xu Mingjin, Nie Jing, Ge Xufeng, et al. Experiment of hydraulic trait of drip irrigation strap under low pressure and the influence of temperature on emitter discharge[J]. China Rural Water and Hydropower, 2010(12):8 – 10. (in Chinese)
25 刘林,陈立,王家生,等. 不同离子浓度下泥沙浓度对絮凝沉降的影响[J]. 武汉大学学报:工学版, 2007, 40(1): 29 – 32.
Liu Lin, Chen Li, Wang Jiasheng, et al. Effect on the flocculation sedimentation velocity in different conditions of cation concentration by concentration of sediments particles[J]. Engineering Journal of Wuhan University,2007, 40(1): 29 – 32. (in Chinese)
26 张德茹,梁志勇. 不均匀细颗粒泥沙粒径对絮凝的影响试验研究[J]. 水利水运科学研究, 1994(增刊 1):11 – 17.
Zhang Deru, Liang Zhiyong. Experiment study of effect of nonuniform fine sediment on flocculation[J]. Hydro-Science and Engineering, 1994(Supp. 1): 11 – 17. (in Chinese)
27 李康勇,牛文全,张若婵,等. 施肥对浑水灌溉滴头堵塞的加速作用[J]. 农业工程学报, 2015, 31(17): 81 –90.
Li Kangyong, Niu Wenquan, Zhang Ruochan, et al. Accelerative effect of fertigation on emitter clogging by muddy water irrigation [J]. Transactions of the CSAE, 2015, 31(17): 81 –90. (in Chinese)