Improving drip irrigation uniformity by boosting the hydraulic performance of drip lateral pressure regulators

Xiaoran Wang[1,2], Chen Zhang[3], Guangyong Li[2*]

(1. *School of Engineering, the Open University of China, Beijing 100039, China*;
2. *College of Water Resources & Civil Engineering, China Agricultural University, Beijing 100083, China*;
3. *Institute of Water Resources for Pastoral Area, Ministry of Water Resources of the PR China, Hohhot 010020, China*)

Abstract: Compared with the use of expensive pressure-compensating drip tapes, installing pressure regulators (PRs) at the inlet of cost-effective non-pressure-compensating drip tapes is obviously a more economical technology to achieve precision agriculture. However, most drip lateral PRs may not meet the requirements of the design and use of complex drip irrigation systems (hilly or large-scale systems), and there is seldom research on their application in drip irrigation systems, both restricting the promotion of this precision agriculture technology. In this paper, two types of PRs (A- and B-type) for complex drip irrigation systems are proposed, and compared with two conventional PRs (C- and D-type) under 9 different pressure and flow conditions of the drip irrigation system. The main advantage of A- and B-type PRs over conventional PRs is that their outlet pressures are scarcely affected by inlet pressure and flow. Therefore, A- and B-type PRs not only cope with large submain pressure differences, but also guarantee irrigation uniformity *CU* up to 90% in drip irrigation systems with different drip-tape lengths (flow range: 350-1400 L/h), while *CU* can be lower than 80% under the same conditions without PRs or using conventional PRs. When designing drip irrigation systems, the use of A- and B-type PRs can allocate greater pressure deviation to the laterals (h_{v2}) to increase the lateral laying length, thus further reducing pipeline network investment. Under the requirements of maximum pressure deviation h_v≤40% and submain pressure deviation h_{v1}≤20%，the results of h_{v2} with A-, B-, C-, and D-type PRs were 30%-35%, 30%-37%, 33%-35%, and 21%-27%, respectively. This research provides a device and method that can improve the irrigation uniformity of drip irrigation systems across a wider application range. Based on this research, users can reasonably select the PRs according to different design standards, significantly enhancing the irrigation uniformity of the system in a cost-effective manner.

Keywords: microirrigation, pressure regulator, engineering application, irrigation uniformity, drip tape
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1 Introduction

As one of the most important precision irrigation technologies, microirrigation is used worldwide because it can supply water and fertilizer to the crop root zone in a highly controlled way and greatly improves irrigation water productivity. According to the Annual Report 2018-19 of the International Commission on Irrigation and Drainage (ICID), the application area of microirrigation was 15.95 Mhm^2 worldwide, and China ranks first among nations using microirrigation, at approximately 5.27 Mhm^2, in which drip irrigation is the most commonly used method. Economical and reusable thin-walled non-pressure-compensating drip tapes are widely used over an area of 3.53 Mhm^2 in the arid and semiarid regions of Northwest China to irrigate profitable food crops, cotton, potatoes, grapes, and horticultural crops[1-5]. However, thin-walled drip tape usually has a low burst pressure and consequently tends to be damaged by the high working pressure under improper management. Moreover, users are prone to operating systems at a lower pressure than designed, which significantly reduces the irrigation system uniformity. Obviously, these drip irrigation systems have difficulty meeting the requirements of precision irrigation.

To achieve precision irrigation, pressure-regulating equipment and pressure-compensating emitters are recommended for use in drip irrigation systems with a poor pressure distribution, such as drip irrigation programs in steep terrain or very large-scale systems. However, due to the construction of decompression pools, the use of pressure relief valves, and the purchase of expensive drip tapes or drip lines with pressure-compensating emitters, drip irrigation systems require a high initial investment, which restricts their frequent application in developing countries[6]. A viable and efficient method that can guarantee the uniformity and safety of a drip irrigation system with economic non-pressure compensating drip tapes needs to be proposed. One solution in the context of investment costs and system performance is to install a pressure regulator (PR) at the lateral inlet of the drip irrigation system. For this purpose, PRs have been designed with a simple configuration comprising a direct acting actuator and a suitable and easy connector for drip tapes, low-cost polyethylene materials, and a low operating (regulating) pressure[7,8].

Most of the current reports on PRs have focused on their use for the main and submain[9-16], and there is little public information on PRs for drip tape inlets. Obviously, in a drip irrigation system,

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Biographies: Xiaoran Wang, PhD, Lecturer, research interest: water-saving irrigation technology, Email: oucwxr@163.com; **Chen Zhang**, PhD, Senior Engineer, research interest: water-saving irrigation technology, Email: swzhangchen@163.com.
***Corresponding author: Guangyong Li**, PhD, Professor, research interest: theories and new technologies of water-saving irrigation. China Agricultural University, No.17, Qinghua East Road, Haidian District, Beijing 100083, China. Tel: +86-10-57519189, Email: ouclgy@163.com.

the upstream pressure and downstream flow conditions of the drip tape inlet PRs, as well as the number of field applications, are different from main and submain PRs. On the one hand, using drip tape inlet PRs changes the inlet pressure of each drip tape in the subunit and offers an opportunity to optimize the pressure distribution; on the other hand, the outlet pressure of PRs is affected by the variations in the inlet pressure and flow rate, and a change in the outlet pressure affects the performance of the system. However, the current research on drip tape inlet PRs is aimed at its own hydraulic performance evaluation or optimization[17-21], and lacks application and analysis at the level of the irrigation system.

For complex drip irrigation systems, such as hills and large-scale drip irrigation systems, variable topography and hydraulic losses lead to large pressure differences in submain pipes, and irregular field shapes lead to different lateral laying lengths. However, most PRs for drip lateral flow may not be able to cope with the complex conditions in which the pressure along the submain and the latera flow vary greatly. The lack of research on high-performance PR products and engineering applications restricts the application scope and promotion potential of this economical and efficient precision irrigation technology.

Correspondingly, this study selected four types of PRs and set up nine typical working conditions for drip irrigation systems (submain pressure difference: 0.08-0.25 MPa, drip tape flow range: 350-1400 L/h). The pressure distribution characteristics and irrigation uniformity of the system were tested and analyzed under these 9 typical drip irrigation conditions, both with and without the installation of these four types of PRs. The aims of this research were to provide a device and method that can improve the irrigation uniformity of drip irrigation systems across a wider application range.

2 Materials and methods

2.1 PR performance comparison

Four types of PRs (denoted A-, B-, C-, and D-type) were used in the experiment, and their nominal preset pressures were 0.06, 0.10, 0.11, and 0.09 MPa, respectively. Among them, A- and B-type PRs were prototypes designed for the application of complex subunits. In this study, an optimization model considering both the outlet pressure and the initial regulation pressure was developed. Based on this optimization model, by appropriately increasing the upstream area and reducing the downstream pressure area of the moving parts (Figure 1), the optimal parameters have been obtained for the purpose of reducing the initial regulation pressure and expanding the regulation range[7]. Furthermore, by configuring springs with different parameters, we obtained two types of PR (A- and B-type) with different preset pressure[7], while C- and D-type PRs were commercially available devices from two manufacturers.

The regulation performance of a total of 120 PRs (with 30 samples randomly selected from each type of PR) was tested in the Laboratory of Irrigation and Drainage, China Agricultural University. Four flow rate conditions of 400, 600, 800, and 1100 L/h were set (Figure 2).

The structures of A- and B-type PRs are shown in Figure 1. They consist of five parts: housing (divided into inlet part and outlet part), regulating seat, spring, and T-shape regulating plunger. By optimizing the configuration relationship between its internal structure and spring parameters[7], these PRs achieve high performance (Figure 2). This PR uses the pressure difference before and after the T-shape regulating plunger, pushing the plunger itself axially to determine the flow orifice, which ultimately controls the friction loss through the regulator.

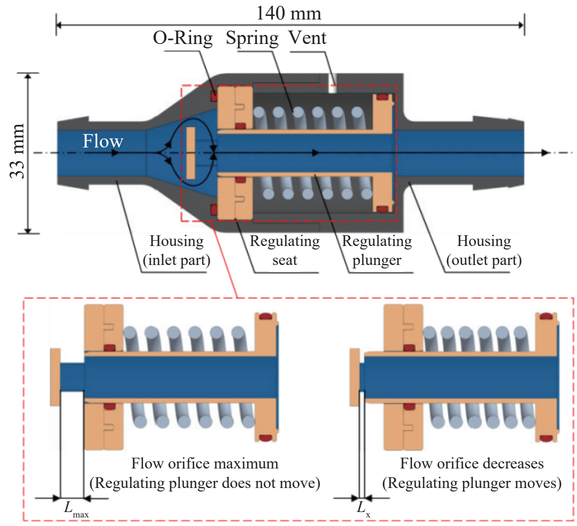


Figure 1 Schematic cross section of the high-performance PR (A- and B-type)

Figure 2 shows that the main advantage of A- and B-type PRs over conventional PRs (C- and D-type) is that their outlet pressures are scarcely affected by the inlet pressure and flow rate, meaning that their measured outlet pressures are approximately equal to the nominal preset pressures. Therefore, A- and B-type PRs have the potential to deal with more complex drip irrigation system conditions and a wider range of applications. In contrast, the performance of the C- and D-type PRs is strongly affected by the flow rate, while that of the D-type PR is also affected by the inlet pressure. These performance deficiencies limit the application range of conventional PRs.

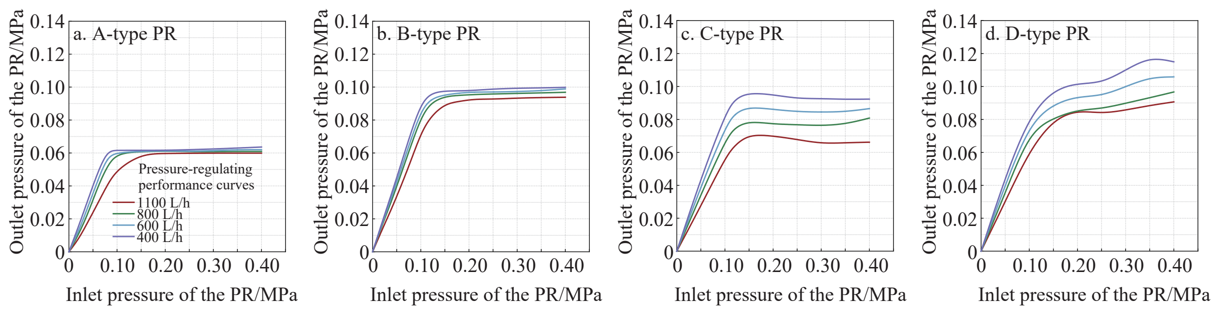
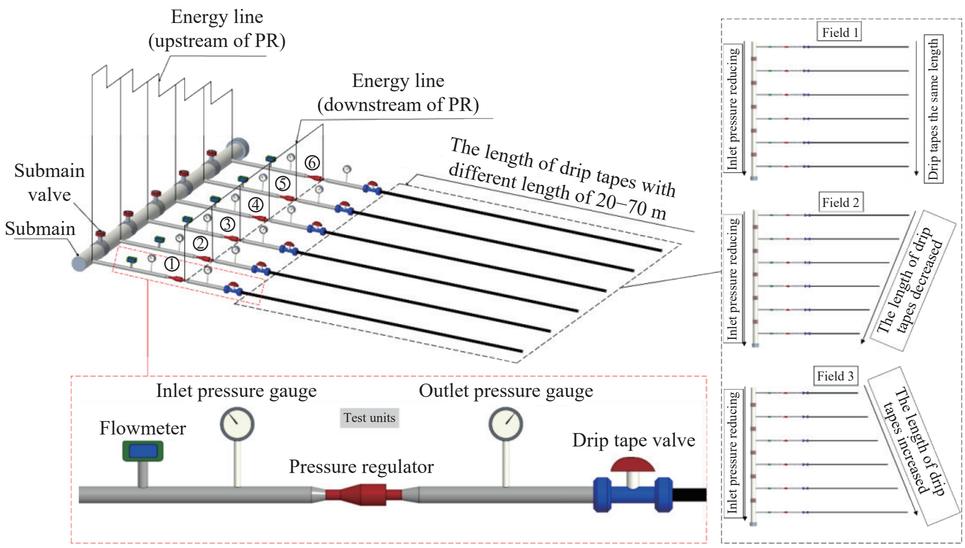


Figure 2 Pressure-regulating performance curves of the four kinds of PRs measured at flow rates of 400, 600, 800, and 1100 L/h

2.2 Field performance evaluation system of PR

A test setup with an adjustable submain pressure and an adjustable drip tape length was adopted to measure the performance characteristics of the PRs in various drip irrigation systems (Figures 3



Note: Field 1, Field 2, and Field 3 represent three kinds of drip irrigation systems with different flow conditions, which are set by changing the lengths of the drip tapes.

Figure 3 Field performance assessment system of PR

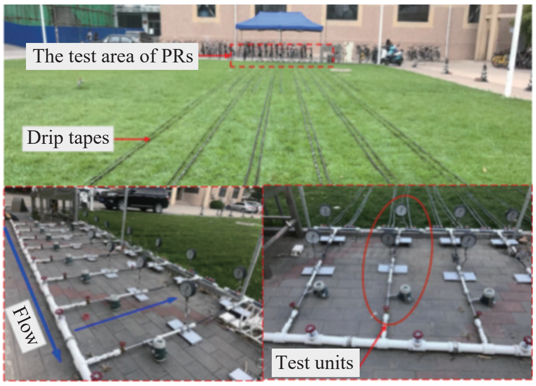


Figure 4 Photos of the real PR test system

and 4). The test system was composed of 6 parallel test units numbered 1–6 according to the distance from the head of the system. A PR was installed at the drip tape inlet of each test unit. The inlet and outlet pressures of the PR were measured by precision pressure gauges with ranges of 0-0.60 MPa and 0-0.25 MPa, respectively, and an accuracy of 0.4% (YB150B, Shanghai, China). The flow rate of the test unit was measured by a turbine flowmeter with a measurement range of 0-1500 L/h and an accuracy of 1% (LWGY-10 m, JBZC, Beijing, China). The pressure difference between adjacent test units was measured by changing the openings of the submain valves to simulate a large pressure difference across the drip tape inlet due to friction loss or steep terrain. The performance indices of the drip tapes (dripper spacing of 0.12 m) were determined according to GB/T 17187-2009[22] as a flow rate of 2.48 L/h (under the condition of operating pressure 0.10 MPa), a flow index of 0.527, a manufacturing dripper deviation of 3.94%, and a burst pressure of 0.20 MPa (Figure 5).

2.3 Field performance evaluation conditions

Three working conditions with different submain pressures (BP1, BP2, and BP3) were set by adjusting the openings of the submain valves (Figure 3). Three working conditions with different flow rates, denoted Field 1, Field 2, and Field 3, were set by changing the lengths of the drip tapes (Figure 3). In total, 9 typical working conditions of the test system were arranged when both the submain valve openings and the lateral drip tape lengths were changed (Table 1). The range of drip tape length settings under different operating conditions is determined based on the applicable

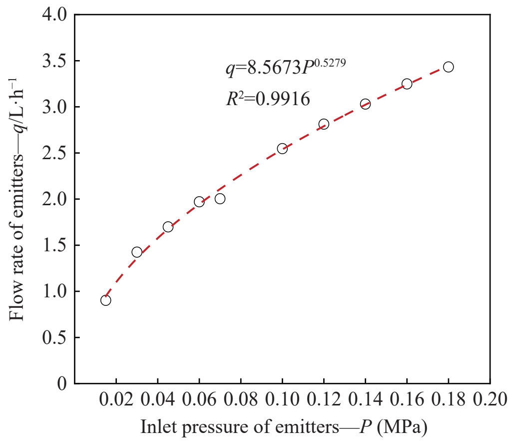


Figure 5 Flow-pressure relationship curves of the emitters

Table 1 Layout conditions of the drip irrigation system

Test system setting conditions					
Drip tape layout condition	Test unit number	Length of drip tapes/m	Submain pressure working conditions		
			BP1	BP2	BP3
			Inlet pressure of PRs/MPa		
Field 1	1	30	0.2	0.3	0.4
	2	30	0.18	0.25	0.35
	3	30	0.16	0.2	0.3
	4	30	0.14	0.15	0.25
	5	30	0.12	0.12	0.2
	6	30	0.12	0.12	0.15
Field 2	1	70	0.2	0.3	0.4
	2	60	0.18	0.25	0.35
	3	50	0.16	0.2	0.3
	4	40	0.14	0.15	0.25
	5	30	0.12	0.12	0.2
	6	20	0.12	0.12	0.15
Field 3	1	20	0.2	0.3	0.4
	2	30	0.19	0.27	0.35
	3	40	0.18	0.24	0.3
	4	50	0.17	0.21	0.25
	5	60	0.16	0.18	0.2
	6	70	0.15	0.15	0.15

Note: BP1, BP2, and BP3 represent the three kinds of submain pressure working conditions; Field 1, Field 2, and Field 3 represent three kinds of drip irrigation systems with different flow conditions, which are set by changing the lengths of the drip tape.

flow range of the PR, while the range of inlet pressure is given according to the applicable pressure range of the PR.

The drip tapes were sized corresponding to three typical drip irrigation systems: a) Field 1 represents simple rectangular subunits in which each drip tape is of equal length. The performance of the PR is affected primarily by its manufacturing deviation and inlet pressure. b) Field 2 represents a drip irrigation system where the lateral drip tape lengths vary from long to short with increasing distance from the pump; that is, the long drip tapes correspond to high inlet pressures, while the short drip tapes correspond to low inlet pressures. In this case, the performance of the PR is affected by the manufacturing deviation, inlet pressure, and flow rate. As the output pressure of the PR increases with increasing inlet pressure and decreasing flow rate, Field 2 yields a favorable layout for the pressure distribution. c) The drip irrigation system in Field 3 is the opposite to that in Field 2 and thus is deemed the most unfavorable layout for the pressure distribution.

During the test, 30 PRs of each type were equally divided into five sets tested as five replicates.

2.4 Field performance evaluation indices

2.4.1 Pressure coefficient of variation of lateral inlet C_V

Ideally, constant pressure is provided among the PRs downstream. In a drip irrigation system, the actual output pressures of the PRs are discretely distributed around the nominal preset pressure due to the influences of manufacturing deviations, inlet pressure and flow rate changes, etc. The coefficient of variation C_V is utilized to characterize the regulation uniformity of the PR outlet pressure and to represent the pressure uniformity of the drip tape inlets (since the PRs are installed at the drip tape inlets), as follows[8,23]:

$$C_V = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(P_i - \bar{P}\right)^2}}{\frac{1}{n}\sum_{i=1}^{n}P_i} \times 100\% \tag{1}$$

where, C_V is the coefficient of variation of the PR outlet pressure/lateral inlet pressure, %; $\bar{P}$ is the average pressure within the statistical range, MPa; n is the number of statistical pressure points; and P_i refers to the pressure value at point i, MPa.

There is no reference C_V for the lateral inlet pressure in existing standards. We use the recommended value given in the PR specifications ISO 10522–1993[24] that C_V should be less than 10% as the acceptable maximum value.

2.4.2 Maximum pressure deviation of drip irrigation design h_v

Pressure deviations of the system h_v, as the primary design criterion, are used to evaluate the PR installation-affected effects (see the Appendix for the detailed calculation of h_v).

Referring to both the technical standard for microirrigation engineering GB/T 50485–2020[25] and the design requirements for microirrigation[26], the general pressure head variation h_v can be divided into two grades: grade I (h_v≤20%) and grade II (h_v≤40%). According to a 1:1 distribution of the submain pressure deviation (h_{v1}) and lateral pressure deviation (h_{v2}), h_{v1} should be less than 10% and 20%, respectively.

2.4.3 Irrigation uniformity *CU*

Christiansen's uniformity coefficient *CU*, estimated from the measured discharges of 25 drippers in the upper, middle, and end parts of each drip tape, is used to evaluate the performance of the drip irrigation system[25] and is calculated as:

$$CU = \left(1 - \frac{\overline{\Delta q}}{\bar{q}}\right) \times 100\% \tag{2}$$

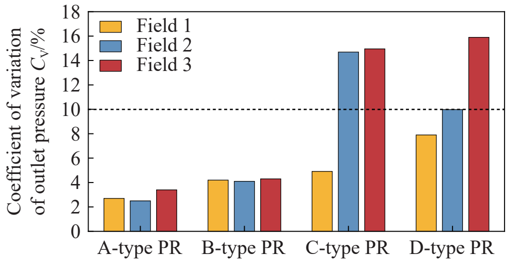
where, $\bar{q}$ is the mean dripper discharge and $\overline{\Delta q}$ is the mean deviation of the dripper discharge.

The *CU* of the drip irrigation system under all working conditions should meet the requirement of *CU*≥80%[25].

3 Results and analysis

3.1 Effect of PRs on the pressure uniformity of lateral inlets

Figure 6 shows the coefficient of variation of the lateral inlet pressure C_V (equivalent to the PR outlet pressure coefficient of variation) after the four types of PRs were installed under different drip irrigation conditions (Table 1). The C_V values of the systems with A-, B-, C-, and D-type PRs were 2.7%, 4.2%, 4.9%, and 7.9%, respectively, under Field 1 conditions; 2.5%, 4.1%, 14.7%, and 9.9%, respectively, under Field 2 conditions; and 3.4%, 4.3%, 15.0%, and 15.9%, respectively, under Field 3 conditions.



Note: Field 1, Field 2, and Field 3 represent three kinds of drip irrigation systems with different flow conditions set by changing the lengths of the drip tapes.

Figure 6 PR outlet pressure coefficient of variation under the conditions of Fields 1, 2, and 3

According to the recommended threshold values for C_V, all four types of PRs were recommended for Field 1 conditions, whereas only A- and B-type PRs were recommended for the conditions of Fields 2 and 3.

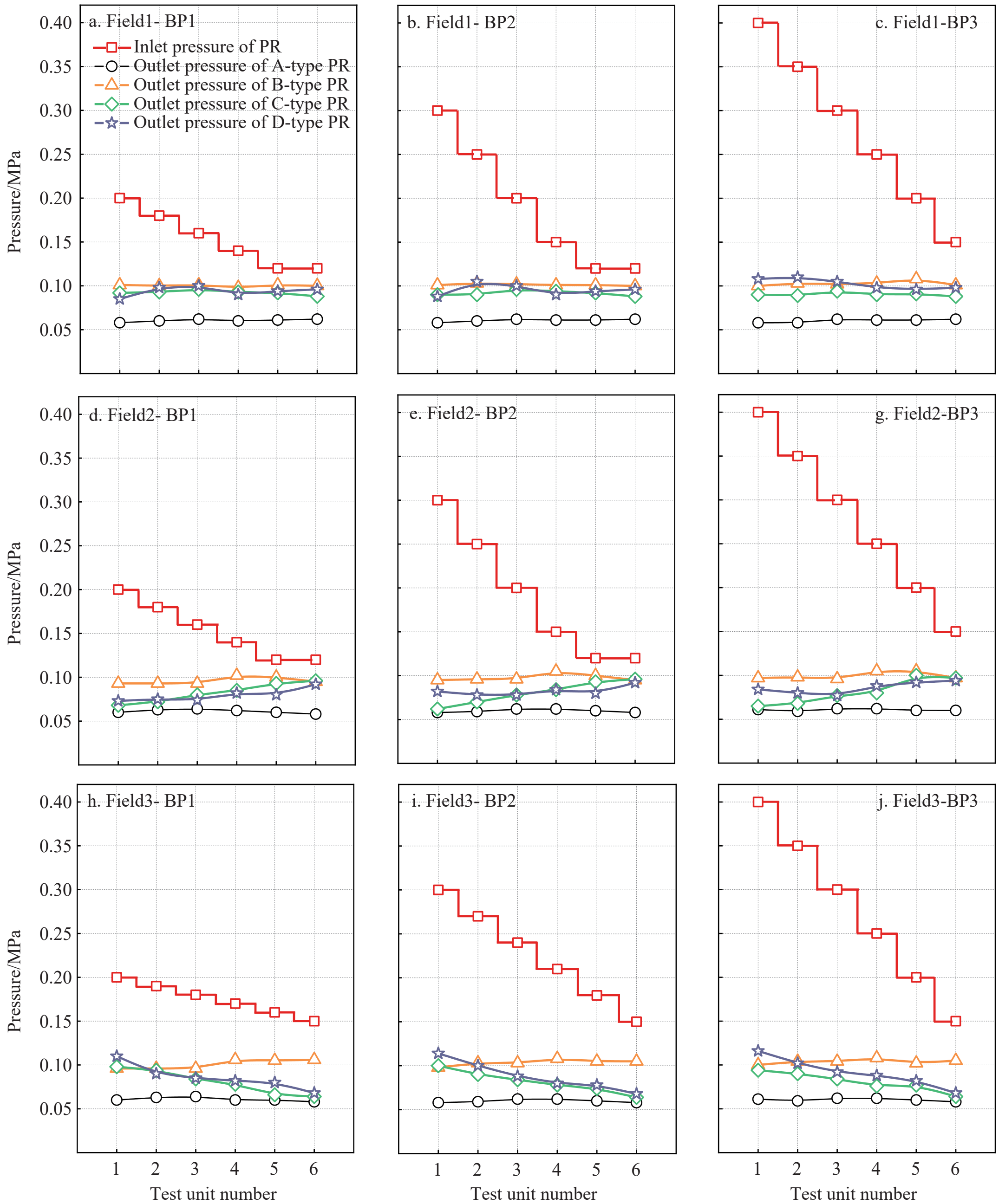
Under the conditions of Field 2, the increase in the outlet pressure caused by a higher inlet pressure neutralizes the decrease in outlet pressure caused by long drip tapes, which was beneficial for reducing C_V and improving the performance of the drip irrigation system using D-type PRs. In contrast, drip irrigation systems using D-type PRs exhibited worse performance under Field 3 conditions.

3.2 Effect of PRs on design pressure deviation distribution

Figure 7 shows the pressure distributions of the submain and PR outlet (lateral inlets) of the drip irrigation system after the four types of PRs (A-, B-, C-, and D-type) were installed under the nine sets of system conditions.

Installing a PR at the drip tape inlet can significantly reduce the influence of the submain pressure difference across the drip tape inlet and make the drip tape inlet pressure more uniform (Figure 7). The maximum pressure head differences across the drip tape inlets in the systems with A-, B-, C-, and D-type PRs are 3-6 kPa, 3-10 kPa, 5-35 kPa, and 12-48 kPa, respectively, while the maximum pressure difference of the submain was 0.08-0.25 MPa. The drip irrigation systems with A- and B-type PRs exhibited the best hydraulic performance, and the pressure lines at the drip tape inlets were the flattest among all nine sets of system conditions.

Table 2 shows the allowable pressure deviations of the submain (h_{v1}) and lateral (h_{v2}) in the drip irrigation system after installing the four types of PRs under the nine sets of system conditions.



Note: BP1, BP2, and BP3 represent the three kinds of submain pressure working conditions; Field 1, Field 2, and Field 3 represent three kinds of drip irrigation systems with different flow conditions, which are set by changing the lengths of the drip tapes.

Figure 7　Pressure distributions of the drip irrigation system after installing the PRs under the conditions of Fields 1, 2, and 3

Table 2　Maximum pressure deviation of the system when installing four kinds of PRs under different drip irrigation conditions

Drip tape layout condition	Submain pressure condition	Pressure deviation of submain h_{v1}/%				Maximum pressure deviation of drip tape h_{v2}/% (I design standard h_v≤20%)				Maximum pressure deviation of drip tape h_{v2}/% (II design standard h_v≤40%)			
		Type of PR				Type of PR				Type of PR			
		A	B	C	D	A	B	C	D	A	B	C	D
Field 1	BP1	7	3	7	17	13	17	13	-	33	37	33	23
	BP2	7	3	7	19	13	17	13	1	33	37	33	21
	BP3	7	8	5	13	13	12	15	7	33	32	35	27
Field 2	BP1	10	9	26	21	10	11	-	-	30	31	15	19
	BP2	7	9	31	16	13	11	-	4	33	31	9	24
	BP3	5	9	32	19	15	11	-	1	35	31	8	21
Field 3	BP1	10	10	31	47	10	10	-	-	30	30	9	-
	BP2	7	9	33	51	13	11	-	-	33	31	7	-
	BP3	7	10	27	53	13	10	-	-	33	30	13	-

Note: BP1, BP2, and BP3 represent the three kinds of submain pressure working conditions; Field 1, Field 2, and Field 3 represent three kinds of drip irrigation systems with different flow conditions, which are set by changing the lengths of the drip tapes; - indicates that design pressure deviation cannot be met under this condition.

According to the results listed in Table 2 and the requirements of the grade I design standard (h_{v1}≤10%) and grade II design standard (h_{v1}≤20%), the following conclusions can be drawn: (a) A- and B-type PRs can meet the requirements of grade I and can be used in the design and optimization of drip irrigation systems under various working conditions. Under the requirements of grade I, the h_{v2} values were 10%-15% and 10%-17%; under the requirements of grade II, the h_{v2} values were 30%-35% and 30%-37%, respectively. (b) Due to the significant impact of flow variation on pressure regulation performance, when the length of the drip tape varies within the irrigation system, h_{v1} of the system with C-type PR almost reached the upper limit of the total pressure deviation h_v. Therefore, it is recommended to be used only in the design of drip irrigation systems with drip tapes of the same length. h_{v2} was 13%-15% for grade I and 33%-35% for grade II. (c) D-type PRs cannot be used in the design of drip irrigation systems with drip tapes of different lengths and should be used with caution in the design of drip irrigation systems even with drip tapes of the same length (since h_{v1} was close to the critical value of grade II).

3.3 Effect of PRs on irrigation uniformity

Table 3 shows the irrigation uniformity of the drip irrigation system with and without PRs installed under different drip irrigation conditions. As Table 3 shows, when PRs were not installed, the *CU* of the drip irrigation system under all working conditions did not meet the requirement of *CU*≥80%[25]. After installing the four types of PRs, the *CU* of the drip irrigation system improved to different degrees, and the security of the system was effectively guaranteed.

Field 1: Under BP1 conditions, the *CU* of the system without PRs was 79%, and the *CU* increased by 17%, 13%, 12%, and 11% after A-, B-, C-, and D-type PRs, respectively, were installed in the drip irrigation system; all of these *CU* values satisfied *CU*≥80%. With an increase in the submain pressure difference (BP2 and BP3 conditions), the *CU* values of the systems with A-, B-, and C-type PRs, whose performance was not significantly affected by changes in the inlet pressure, remained above 90%. The *CU* of the system with D-type PR, whose performance was significantly affected by changes in the inlet pressure, decreased to below 90% but was still higher than 85%.

Field 2: Under BP1 conditions, the *CU* of the system without PRs was 73%, and the *CU* increased by 22%, 22%, 4%, and 5% after A-, B-, C-, and D-type PRs, respectively, were installed in the drip irrigation system; only the drip irrigation systems with A- and B-type PRs satisfied *CU*≥80%. With an increase in the submain pressure difference (BP2 and BP3 conditions), the *CU* values of the systems with A- and B-type PRs, whose performance was not significantly affected by changes in either the inlet pressure or the flow rate, remained above 90%. The *CU* of the system with C-type PR, whose performance was not significantly affected by changes in the inlet pressure but was significantly affected by changes in the flow rate, was still less than 80%. The *CU* of the system with D-type PR rose to 80%-81% because the increase in the outlet pressure caused by the high inlet pressure neutralized the drop in the outlet pressure of the PR caused by the long drip tapes (high flow rate).

Field 3: Under BP1 conditions, the *CU* of the system without PRs was 75%, and the *CU* increased by 20%, 16%, 3%, and 2% after A-, B-, C-, and D-type PRs, respectively, were installed in the drip irrigation system; only the drip irrigation systems with A- and B-type PRs satisfied *CU*≥80%. With an increase in the submain pressure difference (BP2 and BP3 conditions), the *CU* values of the systems with A- and B-type PRs remained above 90%, while the *CU* values of the systems with C- and D-type PRs were still less than 80%. Furthermore, the *CU* values of the systems with D-type PR remained less than 75% under the most adverse (BP3) conditions.

Table 3 Irrigation uniformity of the drip irrigation system for the four kinds of PRs tested

Drip tape layout condition	Submain pressure condition	Maximum pressure difference of submain/MPa	Irrigation uniformity of the drip irrigation system *CU*/%				
			Type of PR				Drip irrigation system does not include PRs
			A	B	C	D	
Field 1	BP1	0.08	96	92	91	90	79
	BP2	0.18	96	97	96	88	drip tape broken
	BP3	0.25	97	97	95	85	drip tape broken
Field 2	BP1	0.08	95	95	77	78	73
	BP2	0.18	97	97	77	80	drip tape broken
	BP3	0.25	97	96	78	81	drip tape broken
Field 3	BP1	0.05	95	91	78	77	75
	BP2	0.15	96	96	77	78	drip tape broken
	BP3	0.25	96	96	78	73	drip tape broken

Note: BP1, BP2, and BP3 represent the three kinds of submain pressure working conditions; Field 1, Field 2, and Field 3 represent three kinds of drip irrigation systems with different flow conditions, which are set by changing the lengths of the drip tapes.

In conclusion, according to the requirement of *CU*≥80%[25], A- and B-type PRs can be simultaneously applied to Field 1, 2, and 3 drip irrigation systems, whereas C- and D-type PRs are suitable only for systems such as Field 1. Moreover, the *CU* values of the system with A- and B-type PRs still reached 90%, even under the condition of a submain maximum differential pressure up to 0.25 MPa and different drip tape lengths. This indicates that in a complex hill drip irrigation system with a large terrain height difference and irregular field shape, the installation of A- and B-type PRs can still help the system achieve precise irrigation.

The research findings suggest that installing high-performance PRs at the inlet of the drip tapes can enhance the safety and irrigation uniformity of non-pressure-compensating drip tapes, while significantly expanding the range of operating conditions suitable for these cost-effective types of drip tape.

4 Conclusions

An economical and efficient device and method for precise irrigation with a wide application range are presented, and its engineering application potential is evaluated. The main conclusions are as follows:

1) Compared with conventional PRs (C- and D-type), high-performance PRs (A- and B-type) are suitable for more diverse drip irrigation conditions. Especially in drip irrigation systems with irregular field shapes and different drip tape lengths, conventional PRs have difficulty performing adequately, while high-performance PRs perform well.

2) Drip irrigation systems designed with high-performing PRs can distribute more pressure deviations to drip tapes than to the submain, allowing the lengths of drip tapes to be increased and reducing the initial investment in the system.

3) The installation of high-performance PRs at the inlets of the non-pressure-compensating drip tapes has the potential to help achieve precise irrigation in complex hilly drip irrigation systems, which cannot be achieved by conventional PRs. In this research, the *CU* of the system with high-performance PRs still reached 90%, even under the condition of a submain maximum differential pressure up to 0.25 MPa and different drip tape lengths. The *CU* can

be lower than 80% under the same conditions without PRs or using conventional PRs.

4) The recommendations for PR usage provided in this manuscript are based on a maximum submain pressure differential of 0.25 MPa and a maximum pressure of 0.40 MPa. This is intended to ensure that users can install and operate the equipment within a broader range of pressures and flow rates. The system with PRs can achieve better performance when the actual submain pressure difference and variation in drip tape flow rates are smaller.

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Appendix

The total system pressure deviation h_v can be calculated following the Chinese technical standard for microirrigation engineering[25].

The flow rate deviation q_v is determined by

$$q_v = \frac{q_{\max} - q_{\min}}{q_d} \times 100\% \tag{A1}$$

The pressure deviation h_v is calculated as follows:

$$h_v = \frac{h_{\max} - h_{\min}}{h_d} \times 100\% \tag{A2}$$

$$h_v = \frac{q_v}{x}\left(1 + 0.15\frac{1-x}{x}q_v\right) \tag{A3}$$

$$h_v = h_{v1} + h_{v2} \tag{A4}$$

where, q_v is the flow deviation of the emitter; $q_{\max}$ and $q_{\min}$ are the maximum and minimum design flows of the emitter, respectively, L/h; q_d is the designed flow of the emitter, L/h; h_v is the pressure deviation of the emitter; $h_{\max}$ and $h_{\min}$ are the maximum and minimum design pressures of the emitter, respectively, m; h_d is the design pressure of the emitter, m; h_{v1} and h_{v2} are the maximum pressure deviations of the submain and the drip tape, respectively, m; and x is the flow index of the emitter.

The flow rate deviation q_v and pressure deviation h_v can also be calculated as follows[26]:

$$q_v = \frac{q_{\max} - q_{\min}}{q_{\max}} \times 100\% \tag{A5}$$

$$h_v = \frac{h_{\max} - h_{\min}}{h_{\max}} \times 100\% \tag{A6}$$

$$h_v = 1 - (1 - q_v)^{\frac{1}{x}} \tag{A7}$$

The standard recommends that q_v be less than 20% for an emitter with an exponent of x=0.5 and an h_v calculated according to Equation (A3) of 40%. (For non-pressure-compensating drip tapes, the flow index is generally greater than 0.5, and here we use 0.5 to represent the theoretically optimal performance achievable by non-pressure-compensating drip tapes.) The standard recommends that a q_v of 10% or less is generally desirable, while a value between 10% and 20% is acceptable; for an emitter with an exponent of x = 0.5, the h_v values calculated according to Equation (A7) are 20% and 40%, respectively.