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One of frontiers in agricultural and environmental biotechnology for the arid regions: Micro-pressure drip irrigation technology theory and practices

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With the goal of reducing cost and energy consumption of drip irrigation systems, the relationship between pressure and cost of drip irrigation systems, as well as the feasibility of reducing the operating pressure, were analyzed. The irrigation quality and reliability of micro-pressure drip irrigation systems were also studied. A theory of micro-pressure drip irrigation technology is proposed, and the components of this type of irrigation system are presented. The results indicate that micro-pressure drip irrigation technology is feasible and that it can significantly decrease initial drip irrigation system cost and recurring operating expenses. Micro-pressure drip irrigation can also overcome some of the clogging problems of conventional drip irrigation systems. It is suggested that micro-pressure drip irrigation will be a topic of importance in the future of agriculture and environmental biotechnology.

Key words: Irrigation, drip irrigation, micro-pressure systems, agricultural and environmental biotechnology, perspective.

INTRODUCTION

Drip irrigation has been used in agriculture for more than 50 years. ICID (2000) recently estimated that the world's drip-irrigated area is 380 thousand hm², or 1.5% of the total irrigated area (Li, 2001; Walker, 2000; Uriel, 2000). Drip irrigation technology was introduced in China in the 1980s, and an industrial standard, "Micro Irrigation Engineering Technical Regulations," was published in 1995. Statistical data showed that the drip-irrigated area was 330 thousand hm² in China in 2004, only 0.5% of the total irrigated area in that country. There is still a large difference compared with the world average of 1.5%. There are only three countries whose drip-irrigated area is more than 10% of the total irrigated area: Israel, with 70%, Cyprus, with 55%, and South Africa, with 17%. In view of the increasing water shortages, as well as the serious waste of water resources in some areas, the potential for application of drip irrigation in China is huge.

The efficiency of drip irrigation is usually the highest among all the major agricultural irrigation technologies. Its principal advantages are high adaptability to topography and potentially high irrigation uniformity, in addition to high water use efficiency (Keller and Bliesner, 2000; Zhao et al., 2009). However in practice, these advantages are not always manifested because of design and operation issues. The major obstacles for the application of drip irrigation are its high initial and operating costs. Therefore, an important topic for current and future research is to reduce the cost of drip irrigation systems without lowering irrigation application uniformity and adequacy. The purpose of this article is to discuss the idea of micro-pressure drip irrigation technology and its technical feasibility.

EFFECTS OF PRESSURE ON SYSTEM COST

A typical drip irrigation system consists of a control head, main lines, manifolds, laterals, and emitters (Merkley and Allen, 2007). The control head includes pumps, filtration

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equipment, valves, fertilizer and chemical injection equipment. In general, the cost of mainlines and manifolds accounts for 35-45% of the total cost, while lateral pipelines are 40-45%, and the control head (consisting of pumps, filters, valves, and related hardware) is 15-20%. Therefore, reducing the cost of main lines, manifolds, and laterals is crucial in lowering the system cost. The cost of mainlines and manifolds is mainly decided by the material price and amount needed. A systematic analysis for drip irrigation system cost was conducted herein as described below.

The cost of mainlines and manifolds is decided by the thickness, diameter, length, and material unit price. The total cost of mainlines, manifolds and laterals is:

$$f = \pi \sum_i^{i=n} [l_i \cdot (d_i \cdot \delta_i + \delta_i^2) \cdot u_i \cdot \rho_i] + f_j \quad (1)$$

Where, f is the total price of mainlines and manifolds, ¥; l_i is the length of pipe i , m; d_i is the inside diameter of pipe i , mm; δ_i is the thickness of pipe i , mm; u_i is the material unit price of pipe i , ¥/g; ρ_i is the density of the material for pipe i , g/ml; and, f_j is the total price of pipe fittings, ¥.

For a given drip irrigation system, the total length of mainlines and manifolds is specified during the design phase. The pipe thickness and diameter are decided according to operating pressure and flow rate. The relation between minimum pipe wall thickness, δ , and pressure is:

$$\delta = \frac{d \cdot p}{2[\sigma]} \quad (2)$$

Where, d is pipe diameter, mm; $[\sigma]$ is tensile strength of the pipe material, MPa; and, p is loop pressure within the pipe, MPa.

The pressure within mainlines and manifolds can be estimated by the velocity-head term of the Bernoulli equation (Wu, 1992):

$$p = \xi \frac{v^2}{2g} \quad (3)$$

In which v is mean velocity of water in the pipe, m/s; ξ is a coefficient related to the pipe material and construction; and, g is the ratio of weight to mass, 9.81 m²/s.

Replacing the mean velocity of water in the pipe, v , with the ratio of flow rate, q , to cross-sectional area:

$$d = \lambda \frac{q^{0.5}}{p^{0.25}} \quad (4)$$

Where, q is flow rate, m³/s; and, λ is a coefficient related to the pipe material and manufacturing process, and is calculated as:

$$\lambda = \left(\frac{\xi}{2g\pi^2} \right)^{0.25} \quad (5)$$

For circular pipe cross sections.

Combining equations (2) and (4) with equations (1):

$$f = \frac{\pi q}{4[\sigma]^2} \sum_i^{i=n} [l_i u_i \rho_i \lambda_i^2 (2\sqrt{p_i}[\sigma] + \sqrt{p_i^3})] + f_j \quad (6)$$

From Equation (6), pressure p , has a direct influence on main and lateral pipe cost. The cost will increase significantly with increasing operational pressure. In the same way, it can also be concluded that the operational pressure is the major factor influencing lateral cost when flow rate is limited. The thickness of lateral pipes can be reduced significantly by reducing the operational pressure, and therefore, the cost. In addition, the cost of pumping is directly proportional to the pressure requirements at the design discharge, such that the cost of pumping increases with increasing operational pressure. The cost of filters and fertilizing devices may also increase with higher operating pressure. Thus, operational pressure is a critical factor influencing drip irrigation system cost. The cost of a drip irrigation system can be reduced significantly by decreasing the operational pressure.

FEASIBILITY OF MICRO-PRESSURE DRIP IRRIGATION TECHNOLOGY

Feasibility of reducing drip irrigation operating pressure

The reduction in operational pressure of a drip irrigation system without proportional changes in main and lateral pipe diameters will result in: 1) A decrease in pipe network flow rate; 2) decrease in irrigation quality; and 3) the maximum length of laterals is reduced and the length of required sub-main pipe will increase. In order to obtain high irrigation uniformity and sufficient irrigation water, the pipe diameter must increase, which results in higher system cost. This problem is addressed in the following paragraphs.

Influence of reduced pressure on pipeline cost

The flow rate equation in the pipes is:

$$q = \frac{\pi}{4} \cdot d^2 \cdot v \quad (7)$$

Combining equations (3) and (7):

$$q = \frac{\pi}{4} \cdot \sqrt{\frac{2g}{\xi}} d^2 \cdot \sqrt{p} \quad (8)$$

When the system pressure p is reduced to $1/m$ ($m > 1$) of the original pressure, the diameter of pipe d will be $m^{1/4}$ of original in order to maintain the flow rate q unchanged.

Combining equations (8) and (6), taking ρ , λ and u as constants (represented by K):

$$f = K \sum_i^{i=n} [l_i \cdot d_i^2 (2p_i[\sigma] + p_i^2)] + f_j \quad (9)$$

Now, suppose the flow rate is constant. When the pressure decreases by $1/m$ times and the pipe diameter increases to $m^{1/4}$ times, the cost of the main and lateral lines is:

$$f' = K \sum_i^{i=n} \left[l_i \cdot d_i^2 \left(2 \frac{1}{\sqrt{m}} p_i [\sigma] + \frac{p_i^2}{\sqrt{m^3}} \right) \right] + f_j \quad (10)$$

For equations (9) and (10), $f' < f$ because $m > 1$. This indicates that, with same irrigation water delivery ability, reducing main and lateral pipe cost can be achieved by decreasing the operational pressure of the irrigation system, while increasing the main and lateral pipe diameter at the same time. It is concluded in the same way that the cost of laterals will decrease when decreasing the operational pressure of the irrigation system, and increasing the diameter of lateral pipes at the same time.

Influence of pressure on maximum lateral length

The maximum length of a drip irrigation laterals is:

$$L_n = s \cdot INT \left(\frac{5.446 \beta_1 \Delta h \cdot h_d \cdot d^{4.75}}{k s q_d^{1.75}} \right)^{0.364} \quad (11)$$

Where, s is the spacing between drip emitters, m; β_1 is the allowable water head deviation allotted on laterals, %; k is a local loss enlarging coefficient; q_d is the emitter design flow rate, l/h; Δh is the lateral water head deviation, m; and, h_d is the emitter design head, m.

The maximum length of the laterals will decrease if the system operational pressure h_d is reduced when the other design parameters and flow rate are unchanged in the same design. In this case, the manifolds should increase to ensure acceptable irrigation application uniformity. Therefore, there is a trend of increasing system cost.

Based on the above analysis, when the pressure decreases by $1/m$ ($m > 1$) times and the pipe diameter increases by $m^{1/4}$ times, the maximum lateral length is:

$$L'_n = s \cdot INT \left(\frac{5.446 \beta_1 \Delta h h_d d^{4.75}}{k s q_d^{1.75}} \right)^{0.364} m^{0.06825} \quad (12)$$

From equations (11) and (12) it can be found that $L'_n > L_n$. That is, the maximum lateral length increases with increasing lateral diameter. The number of laterals will not increase, and the system cost will decrease.

Effects of pressure reduction on drip irrigation

Irrigation performance indicators mainly include irrigation uniformity and emitter discharge variation. Factors that affect these two indicators include manufacturing tolerance, ground slope, water temperature, clogging of emitters and pressure variation. The pressure variations only result in water head variations and have no influences on the other factors. Therefore, the effects of pressure variation on water head variation are the same as the effects on irrigation application uniformity. The hydraulic head variation is:

$$h_v = \frac{h_{\max} - h_{\min}}{h_d} \quad (13)$$

In which, h_v is water head variation; h_{\max} is the maximum operational pressure head within the irrigated area, m; h_{\min} is the minimum operational pressure head within the irrigated area, m; h_d is the design operational pressure head, m.

Within an irrigation plot, pressure variation along the pipeline results mainly from friction head loss and local head losses, namely: h_{\max} , h_{\min} , $h_{f \max}$ and $h_{f \min}$. The total of these losses can be represented by $q \cdot h_f$:

$$\Delta h = h_{\max} - h_{\min} = h_{f \max} - h_{f \min} \quad (14)$$

Where, Δh is the maximum water head, m; and, $h_{f \max}$ and $h_{f \min}$ are the maximum and minimum water head losses, m, respectively. The water head loss is:

$$h_f = \left(1 + \lambda \frac{l}{d} \right) \frac{v^2}{2g} \quad (15)$$

Combining equations (3) and (14), and simplifying:

$$h_f = \left(1 + \lambda \frac{l}{d} \right) \frac{p}{\xi} \quad (16)$$

Reducing the pressure p by $1/m$ times, and increasing the pipe diameter by $m^{1/4}$ times:

$$h'_f = \left(\frac{1}{m} + \lambda \frac{l}{m^{0.25} d} \right) \frac{p}{\xi} \quad (17)$$

Combining equations (15) and (16) with equation (13):

$$\begin{cases} \Delta h = \left(1 + \lambda \frac{l_1}{d}\right) \frac{p}{\xi_1} - \left(1 + \lambda \frac{l_2}{d}\right) \frac{p}{\xi_2} \\ \Delta h' = \left(\frac{1}{m} + \frac{\lambda'_1}{m^{0.25}d}\right) \frac{p}{\xi'_1} - \left(\frac{1}{m} + \frac{\lambda'_2}{m^{0.25}d}\right) \frac{p}{\xi'_2} \end{cases} \quad (18)$$

Where, Δh and $\Delta h'$ are the maximum water head losses before and after a change in pressure, m ; l_1 and l_2 are the distances from the maximum and minimum head loss points to the manifold pipe before a pressure change, m ; l'_1 and l'_2 are the distances from the maximum and minimum head loss points to the manifold pipe after a pressure change, m ; and, ξ_1 , ξ_2 , ξ'_1 , and ξ'_2 , are the structural coefficients of laterals at the maximum and minimum head loss points before and after the pressure change.

Suppose the maximum and minimum head loss points do not change before and after the pressure and pipe diameter change. That means that $l'_1 = l_1$, $l'_2 = l_2$, $\xi'_1 = \xi_1$ and $\xi'_2 = \xi_2$. Then,

$$\frac{\Delta h}{\Delta h'} = \frac{\left(\frac{1}{\xi_1} - \frac{1}{\xi_2}\right) + \left(\frac{l_1}{\xi_1} - \frac{l_2}{\xi_2}\right) \frac{\lambda}{d}}{\frac{1}{m} \left(\frac{1}{\xi_1} - \frac{1}{\xi_2}\right) + \frac{1}{m^{0.25}} \left(\frac{l_1}{\xi_1} - \frac{l_2}{\xi_2}\right) \frac{\lambda}{d}} \quad (19)$$

In equation (19), $\Delta h / \Delta h' > 1$. That is, $\Delta h > \Delta h'$, which means that when the flow rate is unchanged, drip irrigation uniformity can be improved as the system operational pressure is reduced.

However, when the system operational pressure is reduced, the influence of emitter manufacturing tolerance and ground slope on irrigation application uniformity will increase. This influence should be considered in micro-pressure drip irrigation system design. The above analysis shows that drip irrigation system costs can be reduced, in theory, by reducing the operational pressure and increasing the pipe diameter without reducing irrigation application uniformity. This is also the theoretical basis for micro-pressure drip irrigation system design.

Micro-pressure drip irrigation technology

Concept of micro-pressure drip irrigation

The design pressure of traditional drip irrigation is high in order to improve adaptability to ground slope. However, three disadvantages accompany these relatively high pressures: (1) The control head must provide higher pressure for the whole irrigation system to meet the requirement of high irrigation quality; (2) the mainlines and manifolds need to bear pressure heads of 30 - 40 m

of water; and (3) a relatively high system cost that greatly limits its application.

To overcome the disadvantages resulting from high drip irrigation pressure, the concept of micro-pressure drip irrigation system is promoted in this paper. The cost of a drip irrigation system can be greatly reduced by decreasing the operational pressure, which is mainly decided by the design pressure of the water applicators. The design pressure of drip emitters is generally 10 m. However, our measurement results showed that an operational water head of 5 m can meet the requirements of irrigation quality for open field cotton and greenhouse plants. Therefore, the authors refer to drip irrigation with less than 5 m of water head as a "micro-pressure" drip irrigation system. The micro-pressure drip irrigation system is a ground-slope-adaptive and cost-efficient drip irrigation system. It considers the influence of ground slope on irrigation system performance and has reduced energy requirements for pumping. Low operational cost and investment are the two major advantages of this system.

The operational pressure for a conventional drip irrigation system is specified by the maximum ground slope instead of different pressures for different ground slopes. This fact results in excessive pressure on conditions of level ground surface or very small ground slopes and considerable energy may be wasted. This is also a reason why the cost of drip irrigation systems tends to be higher as compared to other irrigation methods. Compared with conventional drip irrigation systems, micro-pressure drip irrigation systems have the advantages of low operational pressure and low system investment cost. However, this does not mean micro-pressure can replace conventional drip irrigation system in all cases. In some cases, only drip irrigation systems with more conventional operating pressures can meet the requirements of difficult topographic conditions (Zhang and Wu, 2005; Zhang, 1991; Niu et al., 2004).

Operational pressure determination of micro-pressure drip irrigation systems

The ground slope and manufacturing variation of emitters must be considered during the design of a drip irrigation system. In China, ground slope is often ignored in practice. Niu et al. (2004) promoted the concept of "ground slope variation rate" and a formula and method to calculate flow rate comprehensively considered head variation, manufacturing variation and ground slope variation (Niu, 2004).

According to Zhang (1991), the flow rate at any point of the drip irrigation system is:

$$q = \frac{k_v}{\lambda_k} (1 + \lambda_h \cdot h_v - 0.5h_v - \lambda_e \cdot e_v)^x q_d \quad (20)$$

Where, h_v is water head variation, %; k_v is the manu-

facturing variation (%); e_v is ground slope variation (%); λ_k , λ_n , and λ_e are probabilities of manufacturing variation, head variation, and ground slope variation at a certain point; x is flow pattern exponent; q and q_d are the actual and design flow rates (m^3/s), respectively.

Let,

$$M = \frac{k_v}{\lambda_k} (1 + \lambda_n \cdot h_v - 0.5h_v - \lambda_e \cdot e_v)^x \quad (21)$$

And, the comprehensive flow rate variation rate is:

$$q_v = \frac{q_{\max} - q_{\min}}{q_d} = M_{\max} - M_{\min} \quad (22)$$

The relationship of comprehensive flow rate variation and ground slope variation can be defined and determined by the above equations. The emitter design pressure, h_d , can be calculated from equations (20) according to the requirement of irrigation quality, and then the operational pressure can be determined.

In addition, Zhang et al. (2005) proposed an equation to determine the design pressure of emitters h_d :

$$h_d \geq 20 \cdot x \cdot \Delta Z \quad (22)$$

Where x is a flow pattern exponent; and, ΔZ is ground slope variation, m.

Zhang et al. (2005) also analyzed ground slope variation, and pipeline and operational costs, and developed a computer program to determine the design operation pressure of emitters using a mathematical optimization method.

All the above methods to determine the design operational pressure are based on the ground slope variation. Therefore, the design of micro-pressure drip irrigation system must first consider ground slope variation, and then the flow rate and flow pattern exponent, to determine the operational pressure and select suitable emitters.

MICRO-PRESSURE IRRIGATION SYSTEM CONSTRUCTION AND EQUIPMENT DEVELOPMENT

Micro-pressure irrigation system construction

The influence of pressure variation on irrigation quality for micro-pressure irrigation systems is significant due to low operational pressures. In addition, the probability of pipe rupture is high due to thin pipe walls. Thus, in order to improve system operation reliability, the operational pressure in each irrigation plots should be in good balance and the occasional significant pressure increasing should be avoided.

A special device (pressure regulator on branch-line) should be installed between manifolds and irrigation plots to avoid pressure variation. This device can eliminate the influence of pressure variation in mainlines and manifolds on the irrigation plots. That is to say that the pressure at the entrance of irrigation plots is constant no matter how the pressure in mainlines and manifolds varies (Liu et al., 2003; Zhang et al., 2005).

Based on the above analysis, the construction of a micro-pressure drip irrigation system can be determined. As shown in Figure 1, a micro-pressure drip irrigation system consists of control head, mainlines, manifolds, pressure adjusting device and laterals. The major difference between a micro-pressure drip irrigation system and a conventional drip irrigation system is the pressure distribution pattern. Consequently, the construction and key equipment performance requirements of the two drip irrigation systems are fundamentally different.

First, water supply and fertilizer injection devices for micro-pressure drip irrigation systems have low requirement for pressure. Moreover, the anti-clogging ability of drip lateral tapes micro-pressure drip irrigation systems is greater than that of conventional drip irrigation systems due to a thinner pipe wall. Therefore, the filtration requirements are less demanding than for traditional drip irrigation systems.

Second, a pressure variation in pipe mainlines and manifolds do not transfer into laterals in the irrigated plots. The pipe network has the same requirements for flow rate but at a lower pressure rating. Therefore, the pipe network has low requirements for pressure rating.

Third, pressure regulation is necessary and it is the critical device in micro-pressure drip irrigation systems. It has two main functions: one is to stabilize the system pressure and the other is to ensure system safety. When pressure variation occurs in mainlines and manifolds, this device will keep the pressure and flow rate constant at the entrance of irrigated plots. When the pressure in mainlines and manifolds is too high, this device will stop the transfer of pressure to the irrigated plots, consuming the excess pressure to protect the system. So, this device is more delicate than conventional pressure regulators, with large discharge and low head.

Finally, the thickness of laterals in micro-pressure drip irrigation systems is very small and the connecting and useful life is quite different compared to conventional drip laterals. It can be made into standard finished products and directly connected to pressure regulators. In summary, although the components of a micro-pressure drip irrigation system are similar to those of a conventional drip irrigation system, the installation and operation is more convenient.

Equipment development

The head of micro-pressure drip irrigation system is less than 5 m and the head of manifolds to irrigation plots is

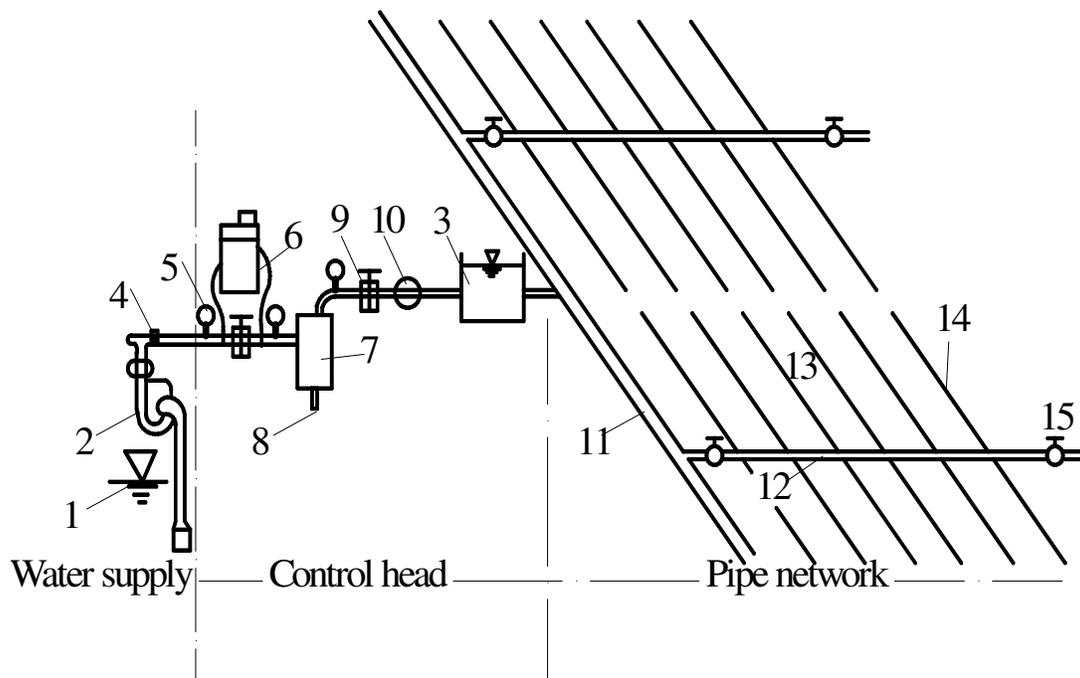


Figure 1. Micro-pressure drip system components. 1 = pump; 2 = water supply; 3 = pressure regulator; 4 = back-flow prevention valve; 5 = pressure valve; 6 = fertilizer injecting device; 7 = filter; 8 = waste-drain valve; 9 = valve; 10 = flow meter; 11 = mainlines; 12 = manifolds; 13 = laterals; 14 = emitters; 15 = flush-out valve.

less than 10 m. Therefore, the whole drip irrigation system pressure will decrease significantly. The pump lift and anti-pressure ability of fertilizer injecting equipment and filter will be reduced. In this condition, large discharge and low-lift pump, low-pressure fertilizer injecting equipment and filter, low-pressure pipe, fittings, and thin-wall drip tape should be developed and used.

Thin-wall drip lateral tapes

Drip irrigation lateral tapes with 0.15 - 0.36 mm wall thickness are specified according to present processing technology and head requirements for drip emitters. Based on an analysis of polyethylene (PE) plastic material performance and head requirements for micro-pressure drip irrigation systems, drip tapes with 0.04 - 0.08 mm wall thickness can meet the operational requirements of micro-pressure drip irrigation systems. Therefore, drip lateral tapes with a wall thickness of less than 0.08 mm should be developed. The emitter design pressures should be from 0.32 to 5.00 m. The cost of drip irrigation system equipped with these thin drip belts will be reduced by 22.5% and the requirement for anti-blocking ability of emitters will decrease due to lower thickness of emitters and shorter useful life.

There are three processing technologies formed at present to produce thin-wall drip irrigation lateral tape.

One is whole flow passage heat-forming technology. This technology first uses a blow-molding machine to produce a plastic film 400 mm wide and 0.04-0.08 mm thick. Second, a vacuum heat pressing/forming machine is used to produce 4 - 5 strips of drip tubing (this is a critical step). Finally, the product is cut into individual strips of drip irrigation tubing.

The second processing technology is built-in strip whole flow passage heat forming technology. First, the whole passage is formed using built-in strips. Second, the strips are agglutinated into drip belts. Finally, the belts are perforated and rolled. The third technology is ultrasonic cold forming technology. First, a plastic film is produced using a blow-forming machine. Second, slip drip emitters or whole passage built-in strips are formed. Then, ultrasonic cold-forming technology is applied to weld the emitters to the plastic film. Finally, the assembly is cut and rolled (Niu et al., 2005).

Low pressure pipe development and their classification standards

The pressure pipe has five grades at present: 0.6, 0.8, 1.0, 1.25 and 1.6 MPa. The diameter ranges from 20 to 630 mm and the size of matched fits ranges from 20 to 250mm. All these parts are not suitable for micro-pressure drip irrigation system. Cheaper and lower pressure (less

than 0.4 MPa) new pipe and fittings need to be researched and developed, including elbows, bypass valves, ball valves and others.

Pressure regulator development

In order to maintain the safety of micro-pressure drip irrigation system and irrigation quality, a pressure regulator with large discharge capacity and low head must be installed at manifold outlets. However, this kind of pressure regulator has not yet been developed. In the future, the pressure regulators with 5 -10m of outlet head for 1-70m³/h (e.g. 1, 2.5, 4, 20, 30 and 70m³/h) of discharge need to be developed. In addition, large discharge and low lift pumps, small fertilizer injection equipment and low pressure filters also need to be developed.

SUMMARY AND CONCLUSION

At present, the design working pressure of typical drip irrigation systems is about 0.1 MPa, which involves large energy waste in most situations. Using theoretical analysis methods to analyze several drip irrigation design aspects, such as system cost, piping network capacity, irrigation adequacy, and others, the authors believe it is feasible to reducing the working pressure of drip irrigation systems to save energy and material costs. In addition to water quality and associated filtration costs, operating pressure is the most important factor to determine the cost of a drip irrigation system. Furthermore, it is possible to reduce the cost of a drip irrigation system by decreasing the operational pressure, without lowering irrigation application uniformity or adequacy. Also, micro-pressure drip irrigation technology is currently feasible, but additional research will be needed to further improve the design of these systems.

Finally, it is concluded that the calculation and determination of micro-pressure drip irrigation operational pressure needs further study. Large-discharge, low-head pressure regulators need to be developed. Material and process technology for ultra-thin drip lateral tape needs to be developed to permit feasible mass production. Pipe classification methods suitable for micro-pressure drip irrigation systems, and new technical standards for engineering design regulations, should be researched. The influences of pressure variation on irrigation application uniformity should be further tested in the field and evaluated (Zhao et al., 2009).

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