·农业水土工程·

双向对冲流滴灌灌水器水力性能与消能效果

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摘 要：双向对冲流滴灌灌水器是 1 种可形成急转流、正反双向流、以及对冲混掺流等加大能量耗散效果的新型灌水器。为研究灌水器的水力性能以及流道几何参数对水力特性的影响，取灌水器几何参数作为因素，采用正交设计安排 25 组试验方案，开展水力性能测试，计算流道的局部损失系数，同时对正交试验结果进行直观和方差分析，建立几何参数与流态指数的回归模型。结果表明，灌水器流态指数为 0.432～0.464，其水力性能良好。单元流道的局部损失系数为 6.698～19.130，显示优越的消能效果。挡水件与分水件最大过水通道宽度对流态指数的影响最大。建立的几何参数与流态指数之间的回归模型 R^2=0.94，且验证表明其估算值与试验值相对误差小于 5%，可可靠地估算流态指数。研究可为双向对冲流滴灌灌水器水力性能预研和评估、结构优化提供参考。

关键词：消能；结构；流速；滴灌灌水器；工作机理；几何参数；局部水头损失

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0 引 言

滴灌是利用灌水器的消能作用将有压水流变成滴水状的 1 种灌水方式[1]，其灌水器是保证灌水质量最关键的元件[2-4]。Gilaad 等[5]指出灌水器的水力性能主要由流道的结构决定。流道结构类型直接影响灌水器流态指数的大小，是反映其水力性能的重要因素[6]。因此，流道形式的优化、创新，以及消能方式的多样性成为灌水器研发的重点。

近年来，国内外很多学者在迷宫流道结构的基础上，提出了一些新的设计思路，并研发了不同流道结构的新型灌水器[7-8]。魏青松等[9-11]设计了新型绕流式流道灌水器，流态指数在 0.5 左右，增强整个流道的扰动效果；李云开、冯吉等[12-14]以分形[15]理论为基础，设计了 1 种流态指数在 0.49～0.53 之间的分形流道灌水器，提高了流体运动的紊流度；De Jesus Souza 等[16]采用聚乙烯管设计了 1 种圆柱形灌水器，有效的提高了灌水器的水力性能。此外，三角绕流灌水器[17-18]、自适应式灌水器[19-20]、微压滴灌灌水器[21]等的设计，都旨在降低流态指数、提高灌水器性能。

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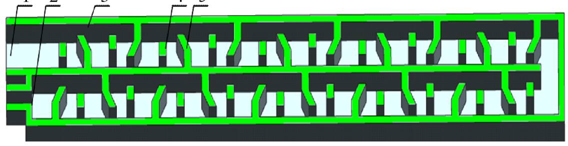
目前普遍使用及新研发的灌水器主要分为 2 类，1 类属于迷宫型流道，在对结构不断的优化与创新过程中，虽然在水力性能方面有很大的提高，但其消能机理基本类似[22-23]，消能方式比较单一，且流态指数基本在 0.5～0.7 之间[24]，水力性能还有很大的提高空间；另 1 类属于压力补偿式[25-27]，其调压稳流效果明显，但是内部起补偿作用的“柔性”调节装置在受到水压反复作用容易变形，降低调压性能，缩短使用寿命。

因此，基于目前灌水器存在消能方式单一化和流态指数偏高的问题，设计 1 种可产生正反双向流混掺等多种局部水头损失形式共同作用的双向对冲流滴灌灌水器，通过试验测试分析灌水器的水力性能以及影响水力性能的几何参数。

1 双向对冲流灌水器流道设计与工作机理

1.1 灌水器设计

本文设计的双向对冲流滴灌灌水器如图 1 所示。



1.进水口 2.出水口 3.流道边壁 4.分水件 5.挡水件
1.Inlet 2.Outlet 3.Flow channel side wall 4. Dividing water device 5.Blocking water device

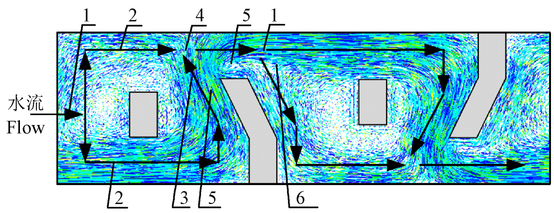
图 1 灌水器结构图
Fig.1 Structure of emitter

双向对冲流灌水器流道结构（图 1）由进水口、流道

边壁、分水件、挡水件、出水口构成，其中分水件与挡水件是形成分流、正反双向流、对冲混掺流以及产生局部水头损失的核心部件。该灌水器的设计采用水力学的管道局部能量损失理论，增加流道断面结构类型的多样性，可以产生水体急转、分流、对冲、混掺等流体运动现象消耗水体能量，从而增大流道的消能稳流能力。

1.2 工作机理

灌水器流道单元分区及工作原理如图 2 所示，灌水器流道分为分流区、突缩区、对冲混掺区、以及突扩区。有压水流首先受到分水件的作用，将整体水流分成沿流道上下边壁的 2 股正向水流，由于流道的突缩作用，产生局部水头损失，消除部分能量；其中 1 股正向水流受到后端挡水件的作用，改变流向，形成反向水流，反向水流受到分水件与挡水件之间的收缩作用，产生局部水头损失；之后在挡水件的齿尖处正反双向水流交汇，形成剧烈的对冲与混掺，产生更大的局部水头损失，消耗大量能量；形成的对冲混掺流流经挡水件齿尖末端再次受到流道的突扩作用，进一步消除多余能量。



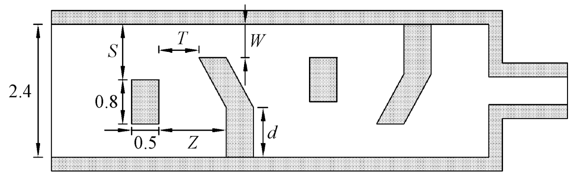
1.分流区 2.正向水流 3.反向水流 4.对冲混掺区 5.突缩区 6.突扩区
1.Divided flow region 2.Forward flow 3.Backward flow 4.Mixed region 5.Sudden shrinkage region 6.Sudden enlargement region

图 2 灌水器流道分区及工作原理
Fig.2 Division and working principle of flow channel of emitter

2 材料与方法

2.1 灌水器流道几何参数与试验方案设计

取分水件与边壁的间距 S、挡水件齿尖与分水件的间距 T、挡水件与边壁的间距 W、挡水件与分水件最大过水通道宽度 Z、挡水件底柱高 d 为流道几何参数，其流道单元几何参数如图 3 所示。



注：S 表示分水件与边壁的间距，mm；T 表示挡水件齿尖与分水件的间距，mm；W 表示挡水件与边壁的间距，mm；Z 表示挡水件与分水件最大过水通道宽度， mm；d 表示挡水件底柱高，mm，下同。
Note: S is distance between dividing water device and flow channel side wall, mm; T is distance between blocking water device tooth and dividing water device, mm; W is distance between blocking water device and flow channel side wall, mm; Z is maximal flow channel width of blocking water device and dividing water device, mm; d is bottom pillar height of blocking water device, mm, same as below.

图 3 灌水器流道单元几何参数
Fig.3 Geometry parameters of flow channel unit of emitter

通常灌水器要求流量[1]≤12 L/h，以流态指数和流量值作为几何参数取值依据，进行预研试验，初步确定几何参数取值范围，预研结果表明流态指数<0.470，流量在预期范围之内，水力性能较好。根据对流态指数与流量预期要求，最终确定灌水器几何参数的取值范围如表 1 所示，同时依据正交设计原则，参考目前普遍研究的灌水器尺寸，流道深度取 0.8 mm，流道单元数为 10，流道相邻单元间距为 1.2 mm。

表 1 灌水器流道几何参数取值
Table 1 Value of flow channel geometry parameters of emitter

水平 Levels	几何参数取值 Geometry parameters values S/mm	T/mm	W/mm	Z/mm	d/mm
1	0.6	0.6	0.6	1.0	0
2	0.7	0.7	0.7	1.1	0.3
3	0.8	0.8	0.8	1.2	0.6
4	0.9	0.9	0.9	1.3	0.9
5	1.0	1.0	1.0	1.4	1.2

注：S 表示分水件与边壁的间距，mm；T 表示挡水件齿尖与分水件的间距，mm；W 表示挡水件与边壁的间距，mm；Z 表示挡水件与分水件最大过水通道宽度，mm；d 表示挡水件底柱高，mm，下同。
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为使试验点整齐、规律、均匀地排列，试验方案具有代表性，结合正交试验设计的“正交性”特点，选 $L_{25}(5^6)$ 进行试验设计，正交设计方案如表 2 所示。

表 2 正交设计方案及试验结果
Table 2 Orthogonal experiment scheme and experimental results

方案 Scheme	参数取值 Parameter value S/mm	T/mm	W/mm	Z/mm	d/mm	流量 Flow rate q/(L·h^{-1})	流量系数 Flow coefficient	流态指数 Flow index 试验值 Experimental value	估算值 Estimated value
1	0.6	0.6	0.6	1.0	0	2.185	0.363	0.458	0.460
2	0.6	0.7	0.7	1.1	0.3	2.311	0.390	0.454	0.455
3	0.6	0.8	0.8	1.2	0.6	2.423	0.418	0.449	0.450
4	0.6	0.9	0.9	1.3	0.9	2.561	0.452	0.443	0.445
5	0.6	1.0	1.0	1.4	1.2	2.721	0.486	0.440	0.440
6	0.7	0.6	0.7	1.2	0.9	2.174	0.377	0.446	0.445
7	0.7	0.7	0.8	1.3	1.2	2.296	0.405	0.442	0.441
8	0.7	0.8	0.9	1.4	0	2.655	0.466	0.443	0.442
9	0.7	0.9	1.0	1.0	0.3	3.165	0.509	0.464	0.460
10	0.7	1.0	0.6	1.1	0.6	2.288	0.388	0.453	0.455
11	0.8	0.6	0.8	1.4	0.3	2.326	0.415	0.440	0.438
12	0.8	0.7	0.9	1.0	0.6	2.613	0.438	0.456	0.456
13	0.8	0.8	1.0	1.1	0.9	2.673	0.457	0.451	0.451
14	0.8	0.9	0.6	1.2	1.2	2.055	0.359	0.445	0.445
15	0.8	1.0	0.7	1.3	0	2.433	0.425	0.446	0.447
16	0.9	0.6	0.9	1.1	1.2	2.419	0.418	0.448	0.447
17	0.9	0.7	1.0	1.2	0	2.859	0.490	0.449	0.448
18	0.9	0.8	0.6	1.3	0.3	2.155	0.379	0.443	0.442
19	0.9	0.9	0.7	1.4	0.6	2.246	0.403	0.438	0.438
20	0.9	1.0	0.8	1.0	0.9	2.887	0.483	0.455	0.456
21	1.0	0.6	1.0	1.3	0.6	2.697	0.497	0.432	0.439
22	1.0	0.7	0.6	1.4	0.9	2.128	0.386	0.435	0.433
23	1.0	0.8	0.7	1.0	1.2	2.311	0.394	0.452	0.451
24	1.0	0.9	0.8	1.1	0	2.679	0.453	0.453	0.453
25	1.0	1.0	0.9	1.2	0.3	2.918	0.502	0.448	0.448

注：q，入口压力 50 kPa 时的流量值；流态指数值由回归模型计算得到。
Note: q, flow rate value under inlet pressure 50 kPa; Flow index is estimated by regression model.

2.2 试件材料与加工

试件模型采用 CAD 软件设计，灌水器分为流道底板和隔水盖板，均选用有机玻璃制作，采用制造精度 0.01 mm、重复定位精度 0.005 mm 的 EM-G32S-X32 型高精密雕刻机同比例切割。

2.3 试验测试方法

试验布置与方法参照 GB/T17187-2009《农业灌溉设备-滴头和滴灌管-技术规范和试验方法》[28]的要求安排设计，每组方案灌水器试件安装 5 个，在 50～250 kPa 工作压力下进行流量测试，每次测试时间均持续 5 min，每个压力点测试 3 次取其平均值。

2.4 指标测定与计算方法

为进一步验证流道的消能效果，根据水力学理论和能量损失叠加原理得到流道的水头损失

$$h_w = \sum h_f + \sum h_j 。\tag{1}$$

由 Darcy-Weisbach 公式可知

$$h_f = \lambda \cdot \frac{l}{4R} \cdot \frac{v^2}{2g} 。\tag{2}$$

局部水头损失为

$$h_j = \xi_j \cdot \frac{v^2}{2g} 。\tag{3}$$

矩形截面流道的水力半径为

$$R = \frac{A}{\chi} = \frac{a \cdot b}{2\,(a+b)} 。\tag{4}$$

由 Blasius 公式可知

$$\lambda = \frac{0.3164}{\mathrm{Re}^{0.25}} 。\tag{5}$$

其中雷诺数 Re 可表示为

$$\mathrm{Re} = 2\rho \cdot v \cdot R/\mu 。\tag{6}$$

式中 h_w 为水头损失，m；h_f 为沿程水头损失，m；h_j 为局部水头损失，m；ξ_j 为局部损失系数；v 为平均流速，m/s；g 为重力加速度，取 10 m/s^2；λ 为摩阻系数；l 为流道长度，m；R 为流道水力半径，m；A 为流道截面面积，m^2；χ 为湿周，m；a 和 b 为流道截面的宽和深，m；ρ 为水的密度，kg/m^3；μ 为动力黏滞系数，N·s/m^2。

由能量守恒原理可知，进口总水头 H 为

$$H = h_w + \frac{v^2}{2g} = \sum h_f + \sum h_j + \frac{v^2}{2g} 。\tag{7}$$

将式（2）、（5）、（6）联立可知

$$h_f = \frac{0.3164\,l}{4R \cdot \left(\dfrac{2\rho \cdot v \cdot R}{\mu}\right)^{0.25}} \frac{v^2}{2g} = \xi_f \cdot \frac{v^2}{2g} 。\tag{8}$$

估算得到 ξ_f 的数量级为 10^{-3}，相对局部损失系数可忽略不计，因此进口总水头可简化为

$$H = \sum h_j + \frac{v^2}{2g} = \sum \xi_j \cdot \frac{v^2}{2g} + \frac{v^2}{2g} 。\tag{9}$$

局部损失系数总和为

$$\sum \xi_j = \frac{2g \cdot H \cdot A^2}{q^2} - 1 。\tag{10}$$

式中 q 灌水器流量，L/h。

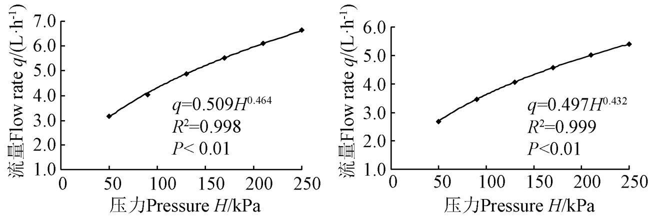
$$q = k \cdot H^x \text{ 即 } \ln q = \ln k + x \cdot \ln H 。\tag{11}$$

式中 k 为流量系数；H 为入口压力或进水口压力，kPa；x 为流态指数。

3 结果与分析

3.1 灌水器流量-压力关系及流态指数分析

正交试验结果如表 2 所示。采用式（11）拟合流量与压力之间的关系，决定系数为 0.998～0.999，回归方程相关性较好。以试验方案 9 和 21 为例（图 4），式（11）拟合值与试验值均方根误差为 0.037 和 0.006 L/h，较准确地反映灌水器压力和流量的关系。用式（11）计算得到 25 组试验方案的流态指数（试验值）0.432～0.464（表 2），表明灌水器的水力性能良好。



a. 试验方案9
a. Experimental scheme 9

b. 试验方案21
b. Experimental scheme 21

图 4　试验方案 9 和 21 的流量-压力关系

Fig.4　Relationship between flow rate and pressure for experimental scheme 9 and 21

3.2 流道消能效果定量分析

25 组试验方案在 5～15 m 时灌水器流道结构局部损失系数为 6.698～19.130，其计算结果见表 3，而传统流道结构的局部损失系数为 2.100～4.840[29-30]，与其相比消能效果有所提高。

表 3　不同方案 5～15 m 时灌水器流道结构局部损失系数

Table 3　Local loss coefficient of emitter with different flow channel structures in different schemes at 5-15 m

方案 Scheme	局部损失系数 Local loss coefficient	方案 Scheme	局部损失系数 Local loss coefficient
1	6.802～7.496	14	13.430～14.271
2	7.546～8.204	15	12.907～14.095
3	10.767～11.588	16	12.016～13.779
4	13.939～14.788	17	10.246～10.958
5	16.017～17.592	18	14.949～15.562
6	13.011～14.283	19	16.334～17.744
7	15.846～16.268	20	8.138～8.729
8	13.898～14.760	21	18.416～19.130
9	6.698～7.281	22	18.060～18.457
10	9.013～9.696	23	9.248～9.968
11	16.170～17.611	24	8.507～9.204
12	7.126～7.713	25	11.241～11.813
13	9.660～10.211		

3.3 流态指数影响因素分析

基于表 2 中流态指数试验值的极差分析结果如表 4 所示。表 4 中极差值表明，各几何参数对流态指数的影响顺序为 $Z>S>d>T>W$。

表 4 正交试验极差分析结果

Table 4 Range analysis results for orthogonal experiment

变量 Variable	流态指数 Flow index				
	S	*T*	*W*	*Z*	*d*
K_1	2.2440	2.2240	2.2340	2.2850	2.2490
K_2	2.2480	2.2360	2.2360	2.2590	2.2490
K_3	2.2380	2.2380	2.2390	2.2370	2.2280
K_4	2.2330	2.2430	2.2380	2.2060	2.2300
K_5	2.2200	2.2420	2.2360	2.1960	2.2270
k_1	0.4488	0.4448	0.4468	0.4570	0.4498
k_2	0.4496	0.4472	0.4472	0.4518	0.4498
k_3	0.4476	0.4476	0.4478	0.4474	0.4456
k_4	0.4466	0.4486	0.4476	0.4412	0.4460
k_5	0.4440	0.4484	0.4472	0.4392	0.4454
极差 Range	0.0280	0.0190	0.0050	0.0890	0.0220

注：K_i 表示任 1 列上水平号为 i 时，所对应的流态指数之和；κ_i 表示 K_i 的算术平均值。

Note: K_i is sum of flow index for level i; κ_i is arithmetic mean of K_i.

进一步分析各参数与流态指数关系的趋势（图 5），可以看出流态指数随 *S*、*Z*、*d* 增大而减小，随 *T*、*W* 增大而增大。

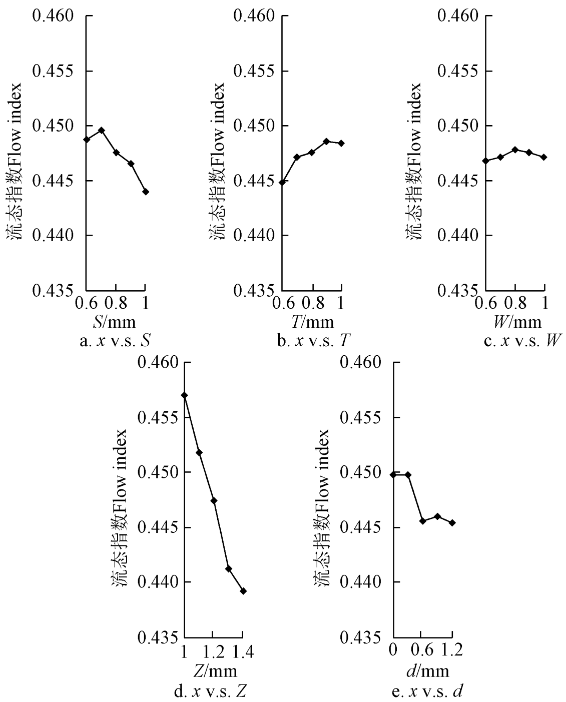


图 5 灌水器参数对流态指数 *x* 的影响

Fig.5 Effect of emitter structure parameters on flow index *x*

方差分析表明（表 5），因素 *S*、*Z*、*d*、*T* 对应 *F* 值大于 3.84，对流态指数影响显著，而因素 *W* 对流态指数影响不显著。

表 5 灌水器参数对流态指数影响的方差分析

Table 5 Variance analysis on effect of emitter structure parameters on flow index

方差源 Variance source	平方和 Sum of square	自由度 Degree of freedom	均方和 Mean sum of square	*F* 值 *F* Value
S	9.51×10^{-5}	4	$2.38\text{E}\times10^{-5}$	9.10
T	4.62×10^{-5}	4	$1.16\text{E}\times10^{-5}$	4.43
W	3.04×10^{-6}	4	$7.60\text{E}\times10^{-7}$	0.29
Z	0.0010858	4	0.000271	104.01
d	0.0001034	4	2.59×10^{-5}	9.91

Note: $F_{0.05}(4,8)=3.84$.

3.4 流态指数预测模型建立及验证

以正交试验结果为基础，采用 Minitab 软件进行一次多元线性回归，令置信度为 95%，计算得到流态指数与各参数之间的回归模型为

$$x=0.5075-0.0126S+0.0086T+0.0012W-0.0462Z-0.0042d。\qquad (12)$$

模型 R^2=0.94（P<0.01），回归效果显著，建立的模型有效。

为进一步验证回归模型的可靠性，在几何参数取值范围内选取 3 组不同的尺寸（表 6），加工试验样机，实物图如图 6 所示。流态指数试验值和回归模型的计算值如表 6 所示。表 6 表明，流态指数的相对误差−0.46%～1.17%，小于 5%，表明式（12）回归模型能准确地反映流态指数与流道几何参数之间的量化关系，可以利用它对该类灌水器流态指数进行预研与评估，一定程度上提高了灌水器试验安排的有效性。

表 6 验证方案及结果

Table 6 Verification scheme and results

组别 Group	几何参数值 Geometry parameters values					试验值 Experiment value	估算值 Estimated value	相对误差 Relative error/%
	S/mm	*T*/mm	*W*/mm	*Z*/mm	*d*/mm			
1	0.6	0.6	0.7	1.2	0.9	0.452	0.447	1.17
2	0.8	0.8	0.6	1.4	0	0.444	0.440	0.824
3	1.0	1.0	1.0	1.4	1.2	0.433	0.435	-0.46

图 6 灌水器流道实物图

Fig.6 Prototype of flow channel of emitter

4 结论与讨论

1）本文设计了 1 种新型双向对冲流滴灌灌水器。通过正交试验获得流态指数为 0.432～0.464，表明其水力性能良好。5～15 m 压力水头下局部水头损失系数为 6.698～19.130，与传统单元流道结构相比消能效果明显提高，表明该类灌水器结构较为合理，有一定的应用前景。

2）流态指数受分水件与边壁的间距 *S*、挡水件齿尖与分水件的间距 *T*、挡水件与分水件最大过水通道宽度 *Z*、挡水件底柱高 *d* 影响显著，受挡水件与边壁的间距 *W* 影响不显著，其中 *Z* 对流态指数的影响最大；流态指数随 *S*、*Z*、*d* 增大而减小，随 *T*、*W* 增大而增大。

3）建立了流态指数预测模型，试验验证其估算值与试验值间相对误差小于 5%，证明了回归模型的准确性和可靠性。

文中着重对新型双向流滴灌灌水器的水力性能以及流道单元关键参数尺寸对流态指数的影响做了深入分析，初步验证了灌水器流态指数基本保持在 0.470 以下，

在水力性能方面得到了一定的提高，并探明几何参数对流态指数的影响，有深入研究的必要。但由于灌水器结构的特殊性，本文只对灌水器结构间的关键参数做了正交分析，而实际影响其性能的因素很多，建议后期研究应综合各种因素将水力性能与抗堵性能统一考虑，并结合灌水器的流场分布与流动状态，对其结构进行合理优化，这将有助于更全面的了解流道结构与流体之间的内在联系，提高灌水器在农业工程中的实际使用价值。

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Hydraulic performance and energy dissipation effect of two-ways mixed flow emitter in drip irrigation

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Abstract: The two-ways mixed flow emitter is a new kind of drip irrigation emitter. The main energy dissipation mechanism is forming many kinds of flow patterns, such as sharp turn flow, two-ways flow and mixed flow to increase more local head loss and eliminate extra inlet pressure. These flow patterns are produced by dividing water device and blocking water device in the flow channel. This structure can enhance the effect of dividing flow, sudden shrinkage, and sudden enlargement of flow channel section. In order to study the hydraulic performance and the effects of geometric parameters on hydraulic characteristic, we arranged 25 experimental schemes according to the orthogonal experimental design method with flow index as evaluation criteria. Five key geometric parameters (distance between dividing water device and flow channel side wall, distance between blocking water device tooth and dividing water device, distance between blocking water device and flow channel side wall, maximal flow channel width of blocking water device and dividing water device, bottom pillar height of blocking water device) were chosen and to flow rate and flow index under different pressures were determined. Laboratory experiments were carried out in State Key Laboratory Base of Eco-hydraulic Engineering in Arid Area, Xi'an University of Technology. Each experimental scheme was set 5 repeats by using high-precision engraving technology and average flow rate was taken to ensure the accuracy of results. Based on the flow rate of each experimental scheme, the flow index was obtained by using multivariable regression method. At the same time, the local loss coefficient of unit flow channel was calculated on the basis of hydraulic theory. In addition, the results of orthogonal experiment were analyzed with intuitive analysis and variance analysis. Then the regression model between geometric parameters and flow index was built. The results showed that the logarithm of flow rate had a good linear relationship with the logarithm of inlet pressure (R^2=0.998-0.999). Based on the relationship, the flow index for the experiment ranged from 0.432 to 0.464, indicating excellent hydraulic performance. The local loss coefficient of unit flow channel was in the range from 6.698-19.130. The energy dissipation effect of two-ways mixed flow emitter was obviously improved compared with the traditional flow channel structure with local loss coefficient of 2.1-4.8. Among the 5 geometric parameters, the maximal flow channel width between blocking water device and dividing water device was the most important influential factor for the flow index, and followed by the distance between dividing water device and flow channel side wall, the bottom pillar height of the blocking water device, the distance between blocking water device tooth and dividing water device. And the effect of these factors on the flow index was significant. However, the distance between blocking water device and flow channel side wall did not significantly affect the flow index. And the regression equation based on the parameters and flow index was well established with R^2 of 0.94 (P<0.01). The regression model was verified using the hydraulic experiments with the other three groups of structure parameters. The relative error of estimated and experimental flow index was from -0.46% to 1.17%, which verified the accuracy and reliability of the regression model. These conclusions can provide theoretical evidence for structure design, pre-research and evaluation of hydraulic performance of two-ways mixed flow emitter.

Keywords: energy dissipation; structure; flow rate; drip irrigation emitter; working mechanism; geometric parameters; local head loss