

RESEARCH ARTICLE

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Impact of water temperature and structural parameters on the hydraulic labyrinth-channel emitter performance

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Abstract

The effects of water temperature and structural parameters of a labyrinth emitter on drip irrigation hydraulic performance were investigated. The inside structural parameters of the trapezoidal labyrinth emitter include path width (W) and length (L), trapezoidal unit numbers (N), height (H), and spacing (S). Laboratory experiments were conducted using five different types of labyrinth-channel emitters (three non-pressure compensating and two pressure-compensating emitters) commonly used for subsurface drip irrigation systems. The water temperature effect on the hydraulic characteristics at various operating pressures was recorded and a comparison was made to identify the most effective structural parameter on emitter performance. The pressure compensating emitter flow exponent (x) average was 0.014, while non-pressure compensating emitter's values average was 0.456, indicating that the sensitivity of non-pressure compensating emitters to pressure variation is an obvious characteristic ($p < 0.001$) of this type of emitters. The effects of water temperature on emitter flow rate were insignificant ($p > 0.05$) at various operating pressures, where the flow rate index values for emitters were around one. The effects of water temperature on manufacturer's coefficient of variation (CV) values for all emitters were insignificant ($p > 0.05$). The CV values of the non-pressure compensating emitters were lower than those of pressure compensating emitters. This is typical for most compensating models because they are manufactured with more elements than non-compensating emitters are. The results of regression analysis indicate that N and H are the essential factors ($p < 0.001$) to affect the hydraulic performance.

Additional key words: emitter structural design; manufacturer's coefficient of variation; emission uniformity.

Introduction

Drip irrigation is considered to be the most efficient irrigation method because it can distribute water uniformly, control the amount of water applied precisely, reduce evaporation and deep percolation, and minimize salinity effects (Batchelor *et al.*, 1996; Ayars *et al.*, 1999).

In drip irrigation systems, multiple outlet pipes have been used to distribute water in irrigated areas. The

discharge at each equally spaced outlet is assumed to be constant, and the resulting outflow along the lateral should be as uniform as possible (Scaloppi & Allen, 1993). Drip irrigation systems consist of small emitters, either buried or placed on the soil surface, discharging water at a controlled rate. Water is applied frequently to prevent moisture stress in the plant by maintaining favorable soil moisture conditions (Cook *et al.*, 2003).

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Received: 12-09-13. Accepted: 17-06-14.

Abbreviations used: CV (manufacturer's coefficient of variation of emitters); EU (emission uniformity); FRI (flow rate index); H (trapezoidal unit height); k (discharge coefficient); L (path length); MLR (multiple linear regression); n (total number of emitters along the lateral); \bar{n} (number of emitters per plant); N (trapezoidal unit numbers); P (operating pressure); P_a (average or design pressure); P_{min} (minimum pressure); q (emitter discharge rate); $q_{15^\circ C}$ (emitter discharge rate at the reference water temperature of 15°C); q_i [discharge rate of emitter (i)]; q_{max} (maximum emitter discharge rate); q_{min} (minimum emitter discharge rate); q_t (emitter discharge rate at the test water temperature); q_{var} (emitter discharge rate variation); \bar{q} (average value of emitter discharge rate); S (trapezoidal unit spacing); S_d (standard deviation of emitter discharge rate); T_w (water temperature); W (path width); x (discharge exponent).

A poorly designed and managed drip irrigation system results in non-uniform water distribution, and non-uniform irrigation results in both less crop development and less yield (Bhatnagar & Srivastava, 2003). However, it is possible to achieve high irrigation water uniformity with drip irrigation systems having the potential to apply small water amounts with the desired interval, and at a depth of the crop root zone (Decroix & Malaval, 1985). But the success of drip irrigation systems depends directly on the operation of the drip emitters (Al-Amoud, 1995).

The emitter is one of the key parts and plays a significant role in drip irrigation systems. It is designed to let out the pressurized water in pipes to drop into the soil slowly and uniformly through energy dissipation by its internal structure. The structure has a great effect on the hydraulic performance of emitters (Nakayama & Bucks, 1986).

The hydraulic performance of emitters has been characterized by empirically determining discharges as a function of operating pressure (Keller & Karmeli, 1974):

$$q = k P^x \quad [1]$$

where q is the emitter discharge rate in $L h^{-1}$; k is the discharge coefficient in $L h^{-1} kPa^{-x}$ that depends on the emitter morphology and behavior; P is the operating pressure in kPa ; x is the discharge exponent that is an index to evaluate the emitter's hydraulic performance (Karmeli & Keller, 1975; ASABE, 2005). The hydraulic performance of emitters is highly influenced by the x ; to some extent, the x is decreased with an increase of pressure (Qingsong *et al.*, 2010). According to the x , emitters can be classified as laminar for $x \approx 1$, turbulent when x ranges between 0.4 and 0.8, and self-compensating when x is close to zero (Evans *et al.*, 2007). Transitional flow characteristics of labyrinth-channel emitters have indicated that the flow inside emitters is turbulent under practical range of pressures (Evans *et al.*, 2007; Zhao *et al.*, 2009). The emitters with a square labyrinth cross-section perform better than labyrinth emitters with a rectangular section (Zhiqin & Lin, 2011).

Emitters with labyrinth channels are used because of their simple structures and low cost. A design theory of labyrinth channels with trapezoidal structures for emitters was established based on regression analysis of hydraulic parameters (Wei *et al.*, 2007). Currently, most point-source emitters have labyrinth flow paths to control the application of water from tubing and

some tapes. The pressurized water in pipes drops into the soil slowly and uniformly through the emitters' labyrinth channels. The structure of labyrinth channels, therefore, is the most important section affecting emitters' performances (Zhang *et al.*, 2011). Investigation of practical flow of water and possible clogging of labyrinth channel emitters through computational fluid dynamics, based on the two-phase theory, shows that it could provide a feasible method for anticlogging optimal design of labyrinth-channel emitters (Wei *et al.*, 2009).

Temperature variations influence water properties, especially viscosity. This may be a significant factor affecting emitter flow channel (Rodriguez-Sinobas *et al.*, 1999). Geometry in the flow channel also may be affected. Karmeli & Keller (1975) suggested that the discharge sensitivity to water temperature would be minimal in emitter where the flow regime is turbulent, *e.g.*, nozzle vortex and labyrinth type emitters. The relationship between the emitter discharge and temperature change can be expressed as a linear function (Al-Amoud & Al-Saud, 2005). Different dimensions of labyrinth emitter can produce various discharge rates depending on water pressure (Evans *et al.*, 2007).

Uniformity coefficients that are used as drip irrigation design criteria include the emitter discharge rate variation (q_{var}), manufacturer's coefficient of variation (CV), emission uniformity (EU), and discharge exponent (x). Each emitter model is characterized by a CV . Zapata *et al.* (2013) reported that the CV of discharge within the irrigation events was 12%, while the CV of discharge between the different irrigation events was 10%. In an actual field condition, there will always be emitter discharge differences, even under constant water pressure conditions. This variation is caused by small errors in the manufacturing process that result in discharge differences from one emitter to the next. Any difference in the flow channel area or shape from a standard size will cause q_{var} . The design of the drip irrigation system is crucial to merit high values for the EU . It is necessary to limit the variation of the pressure head along the lateral to obtain a certain EU value. Other factors affecting q_{var} is field topography, water temperature changes, variability in soil hydraulic characteristic, emitter spacing, and emitter clogging (Nakayama & Bucks, 1986; Mizyed & Kruse, 1989).

In this system, the most valuable outcome of the evaluation process is irrigation uniformity. The uniformity coefficients are indicators of how equal or

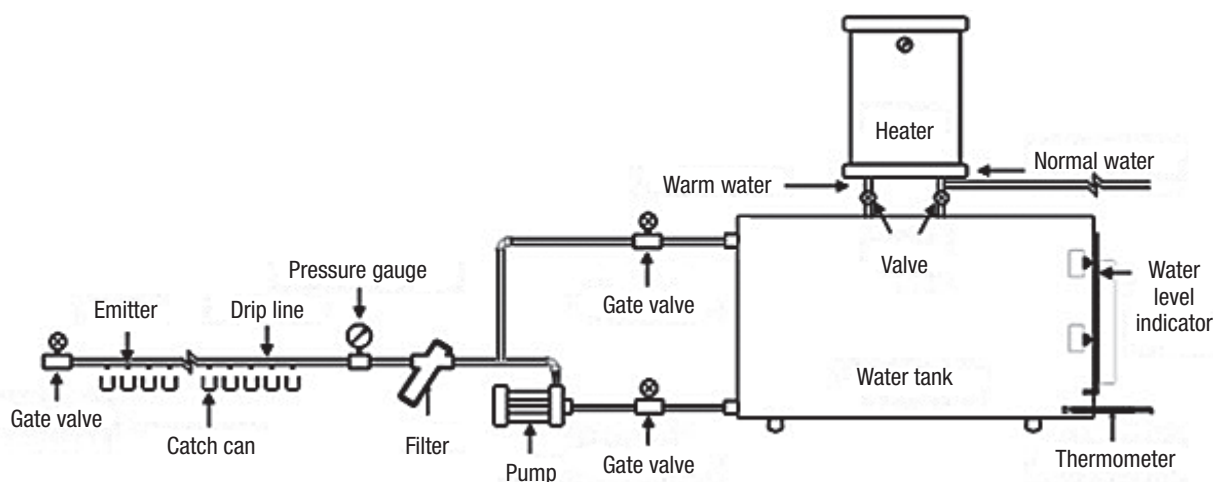


Figure 1. Experiment layout of the measured emitter discharge rate in the laboratory.

unequal are the application rates resulting from the delivery devices. Uniformity of the system is usually a combination of measuring the variability of emissions from individual emitters and pressure variations within the entire system (Nakayama & Bucks, 1986). Griffiths & Lecler (2001) state that pressures and emitters discharge rates are two important aspects in drip irrigation which can influence uniformity adversely.

When the pressure variations down the laterals are combined with the discharge variation from emitters, these readings can be used to quantify whether q_{var} is due to hydraulics or emitter blockages. If emitter blockages are found to be a major problem, methods to help prevent the situation worsening further are recommended. The causes of the blockages can include poor design leading to inadequate flushing velocities, incorrect filtration, poor water sources and pump intake arrangements, and/or inadequate or inappropriate water treatment and routine maintenance (ASABE, 2005).

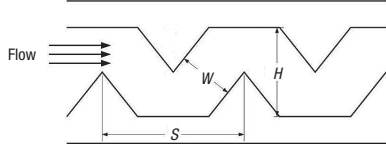





Because of a lack of water resources, water shortage has become the largest restricting factor for agricultural development. A water device (*i.e.*, emitter) in drip irrigation is one of the most effective elements in water-saving. Therefore, it is necessary to study the section form of the emitter and also consider the effects of changes in water temperatures and operating pressures on the performance of the emitter. The goals of our study were to evaluate hydraulic performance of labyrinth emitters at variations of water temperatures and operating pressures and to analyze the influences of the structural design of the labyrinth emitter on the hydraulic performance.

Material and methods

Experimental procedure

The experiments of hydraulic performance were carried out using five types of drip emitters, all of which adopt a long-path labyrinth channel emitter of trapezoidal-shaped units assembled inside the drip line system. The experimental layout was assembled to support the drip lines, as shown in Fig. 1. One drip line was positioned along the framework and a water tank of $50 \times 50 \times 50$ cm dimensions was placed on a stand to supply water for the drip line. Temperature gauges were installed on the walls of the tank to assure that the water temperature was the same throughout the tank. A small centrifugal water pump of 1 hp was used to provide system pressure, and the water pressure was regulated manually through a pressure-regulating valve and a bourdon pressure gauge with accuracy of 10 kPa. A screen filter was fitted just after the pump. According to the practical operating condition of the drip irrigation system, pressure values were made from 50 kPa to 100 kPa at 25 kPa intervals, and then from 100 kPa to 300 kPa at 50 kPa intervals. Water temperature was controlled electronically through a thermostat unit. The values of water temperature were taken from 15°C to 45°C at 10°C intervals. Tests for each type of emitter were conducted alone to avoid possible experimental errors. The water pressure was regulated from low to high step-by-step at the minimal value of water temperature (15°C). During experiments, catch cans were placed along the drip line directly below

Table 1. Dimensions and characteristics of emitters

Emitter code	Emitter labyrinth shape	Drip line dimensions (mm)		Structural parameters					Nominal emitter flow rate (L h ⁻¹)	Operating pressure (kPa)	
		ID ^a	t ^b	N ^c	L ^d	W ^e	H ^f	S ^g			
											
E1		16	1.1	61	53.59	1.22	2.37	2.40	4.0	70-207	
E2		16	1.1	22	48.00	2.03	5.56	4.02	8.0	50-400	
E3		16	1.1	52	234.84	1.88	3.48	3.73	3.0	50-400	
E4		16	0.9	22	75.43	2.29	5.14	4.29	3.5	50-400	
E5		16	1.1	12	28.92	1.69	3.51	2.96	4.0	50-400	

^a Inside diameter. ^b Thickness. ^c Number of units. ^d Length of water path (mm). ^e Path width (mm). ^f Unit height (mm). ^g Unit spacing (mm).

emitters to collect water from emitters after the water pressure reached a stable value. The system was operated for about 30 minutes, at least, to stabilize lateral pressure and emitter discharge. The individual discharge rate was measured at 50 adjacent emitters located at the upstream end of the drip line according to ASABE standards (ASABE, 2005). Discharge rates were then calculated using a weighing method. After completing the readings of one type of emitter under all operating pressures, the water temperature was regulated from the lowest value of 15°C to 25°C and then was raised step-by-step until reaching the highest value of 45°C. This procedure was repeated with other emitters until all the tests were completed. Measurements were repeated three times for each water temperature and operating pressure combination.

Emitter structural design

The emitter flow path (trapezoidal channel units) consisted of the inlets, channels units, and outlets. Every emitter channel has a different structure; therefore,

each emitter is especially characterized by structural design for path width (*W*) and length (*L*), trapezoidal unit numbers (*N*), height (*H*), and spacing (*S*). An optical microscope (Kang *et al.*, 2003) was employed to measure its dimensions. The structural design parameters and product pictures of the emitters are given in Table 1.

Hydraulic performance criteria of emitters

The values of the discharge rate were estimated from experimental procedures to calculate hydraulic performance, as follows:

— Flow rate index (*FRI*). To determine the effect of water temperature on emitter discharge, a *FRI* was calculated assuming a reference temperature of 15°C, using the following equation (ASABE, 2005):

$$FRI = \frac{q_i}{q_{15^\circ C}} \quad [2]$$

where *q_i* is the emitter discharge rate at the test water temperature, and *q_{15°C}* is the emitter discharge rate at the reference water temperature of 15°C.

— Emitter discharge rate variation (q_{var}); q_{var} is usually estimated by comparing maximum and minimum emitter discharges using the Eq. [3] (Wu & Gitlin, 1983):

$$q_{\text{var}} = \left(\frac{q_{\text{max}} - q_{\text{min}}}{q_{\text{max}}} \right) \times 100 \quad [3]$$

where q_{max} and q_{min} are the maximum and minimum emitter discharge rates.

— Manufacturer's coefficient of variation of emitters (CV). The manufacturer's variation is the variation in emitter discharge from a random sample of emitters operated at the same pressure (Nakayama & Bucks, 1986), and expressed as:

$$CV = \frac{S_d}{\bar{q}} \times 100 \quad [4]$$

$$S_d = \sqrt{\frac{\sum_{i=1}^n (q_i - \bar{q})^2}{n-1}} \quad [5]$$

where S_d is the standard deviation of emitter discharge rate; \bar{q} is the average value of emitter discharge rate; n is the total number of emitters along the lateral; and q_i is the discharge rate of emitter (i).

— Emission uniformity (EU). EU describes how uniformly the overall system can distribute water from each emitter (Karmeli & Keller, 1975) and could be estimated from:

$$EU = \left(1 - \frac{(1.27 CV)}{\sqrt{\bar{n}}} \right) \times \frac{q_{\text{min}}}{\bar{q}} \quad [6]$$

where \bar{n} is the number of emitters per plant.

These criteria results were compared with the ASABE (2005) field micro-irrigation performance standards. The general performance evaluation criterion for q_{var} are: <5%, excellent; 5-10%, very good; 10-15%, fair; 15-20%, poor; and >20%, unacceptable. The CV criteria are: <0.10, good; 0.10-0.20, average; and >0.20, unacceptable. EU criteria are: >90%, excellent; 80-90%, good; 70-80%, fair; 60-70%, poor; and <60%, unacceptable.

Statistical analysis

Determining an appropriate relationship between a response variable and a set of variables is one of the usual problems in statistical analysis. Regression ana-

lysis is commonly used to describe these relationships quantitatively. Multiple linear regression (MLR) analysis (regression tool of Microsoft Excel) among operating pressure, water temperature, and structural design emitter parameters was used to verify the significant effect ($p < 0.05$, <0.01, or <0.001) of these variables on emitter discharge and hydraulic performance. Those relationships are expressed as a linear or a straight-line equation.

Alongside the estimated regression coefficients, the regression standard error (SE) and the determination coefficient (R^2) value were examined, in order to judge whether the best-fitting line does in fact fit the data to an adequate degree. The SE gives us a first index on how well the fitted equation fits the sample data. The SE is sensitive to the units of calculation of the dependent variable. The R^2 gives a measure of the 'goodness of fit' of the estimated equation.

Results and discussion

Emitters' hydraulic characteristics at various operating pressures and water temperatures

Determination of discharge equation parameters

The measured discharges of all emitters under different operating pressures at various water temperatures are shown in Fig. 2. The figure shows a general trend of linear increase in discharge rates as pressure increases with all tested emitters, except E4 and E5, where discharges show a slight increase due to an increase of operating pressure at all test water temperatures. Discharges were relatively the same at all operating pressures due to the pressure compensating function of E4 and E5 emitters. On the other hand, E1, E2, and E3 emitters were non-pressure compensating emitters where discharge was generally increased by 131.1%, 117.3%, and 130.0%, respectively, as operating pressure increased from 50 to 300 kPa, in agreement with Bralts *et al.* (1981) and Özekici & Bozkurt (1999). As for compensating emitters (E4 and E5), discharge was increased slightly by 4.4% and 2.5%, respectively, at the same test operating pressures range (Madramootoo *et al.*, 1988; Özekici & Bozkurt, 1999). Emitter discharge and operating pressure relationships for the tested emitters (Fig. 2) product fit a standard power

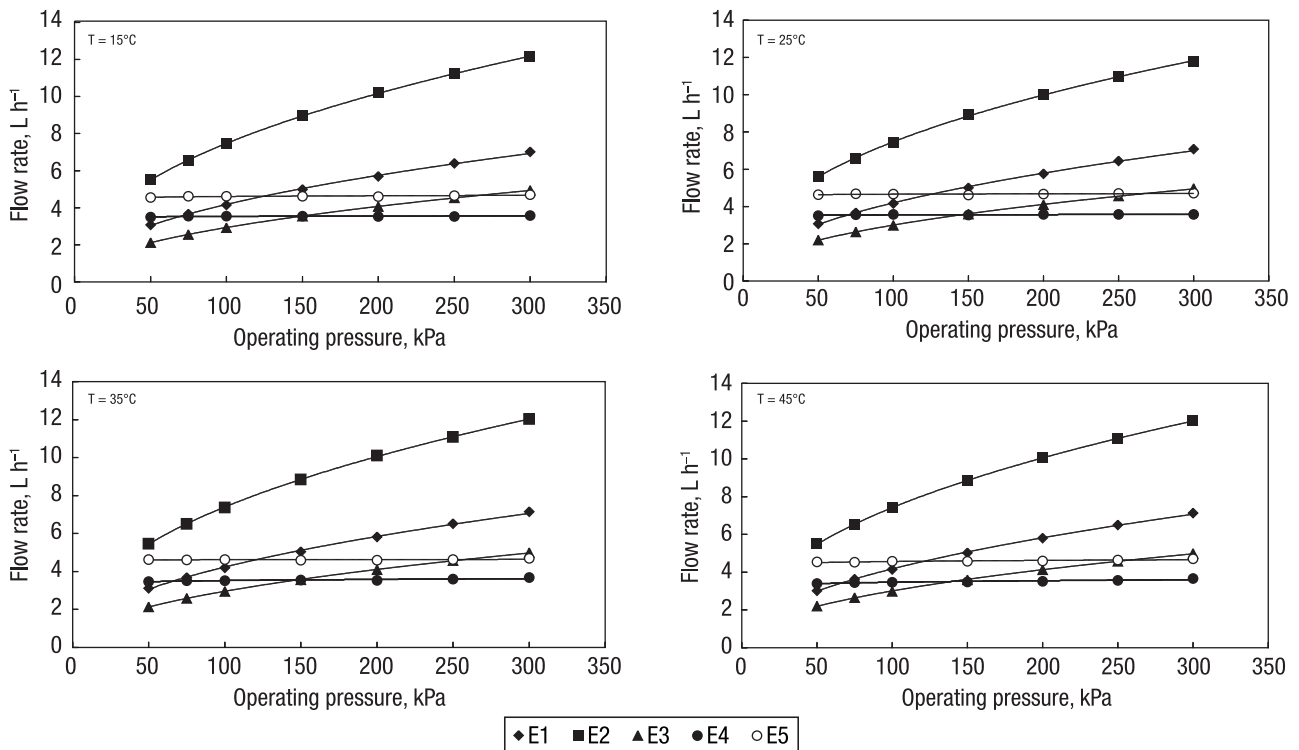


Figure 2. Discharge rates versus different operating pressure for tested emitters at various water temperatures.

function as expressed by Eq. [1]. The values of emitter coefficient (k) and exponent (x) are summarized for the five emitters in Table 2. Average k ranged from 0.35 of E3 to 1.00 of E2 for non-compensating emitters. The corresponding values for E4 and E5 (compensating emitters) are 3.25 and 4.41, respectively. The average x values of the non-compensating emitter fall within 0.44 of E2 to 0.47 of E1, while average compensating emitters' x values are 0.02 of E4 and 0.01 of E5. According to ASABE standards, the flow of the non-compensating emitters are fully turbulent with an x level of about 0.5, indicating that a pressure variation of 20% will result in a flow variation of approximately 10%. However, x values were close to zero for E4 and E5, which are categorized as fully compensating emitters, where pressure variations cause little discharge variation. Regression analyses for each emitter's discharges in Table 2 showed that the non-compensating emitters (E1, E2, and E3) were highly significantly affected ($p < 0.001$) and very significantly affected ($p < 0.01$) for compensating emitters (E4 and E5) at test operating pressures. Higher x values for the non-compensating emitters showed that the flow rates had sensitivity to pressure variation in the system compared to compensating emitters.

Table 2. Values of k and x for tested emitters at various water temperatures

Emitters codes	Water temperature (°C)	k	x	p value
E1	15	0.50	0.46	4.65×10^{-5}
	25	0.49	0.47	4.35×10^{-5}
	35	0.50	0.46	4.36×10^{-5}
	45	0.46	0.48	3.73×10^{-5}
E2	15	0.96	0.44	6.35×10^{-5}
	25	1.09	0.42	8.96×10^{-5}
	35	0.96	0.44	6.55×10^{-5}
	45	0.99	0.44	6.86×10^{-5}
E3	15	0.33	0.47	4.29×10^{-5}
	25	0.37	0.45	5.39×10^{-5}
	35	0.34	0.47	4.34×10^{-5}
	45	0.37	0.46	5.18×10^{-5}
E4	15	3.42	0.01	3.70×10^{-3}
	25	3.46	0.01	3.74×10^{-3}
	35	3.14	0.03	3.21×10^{-3}
	45	2.97	0.03	3.00×10^{-3}
E5	15	4.35	0.01	3.55×10^{-3}
	25	4.53	0.01	3.87×10^{-3}
	35	4.56	0.01	3.75×10^{-3}
	45	4.19	0.02	3.36×10^{-3}

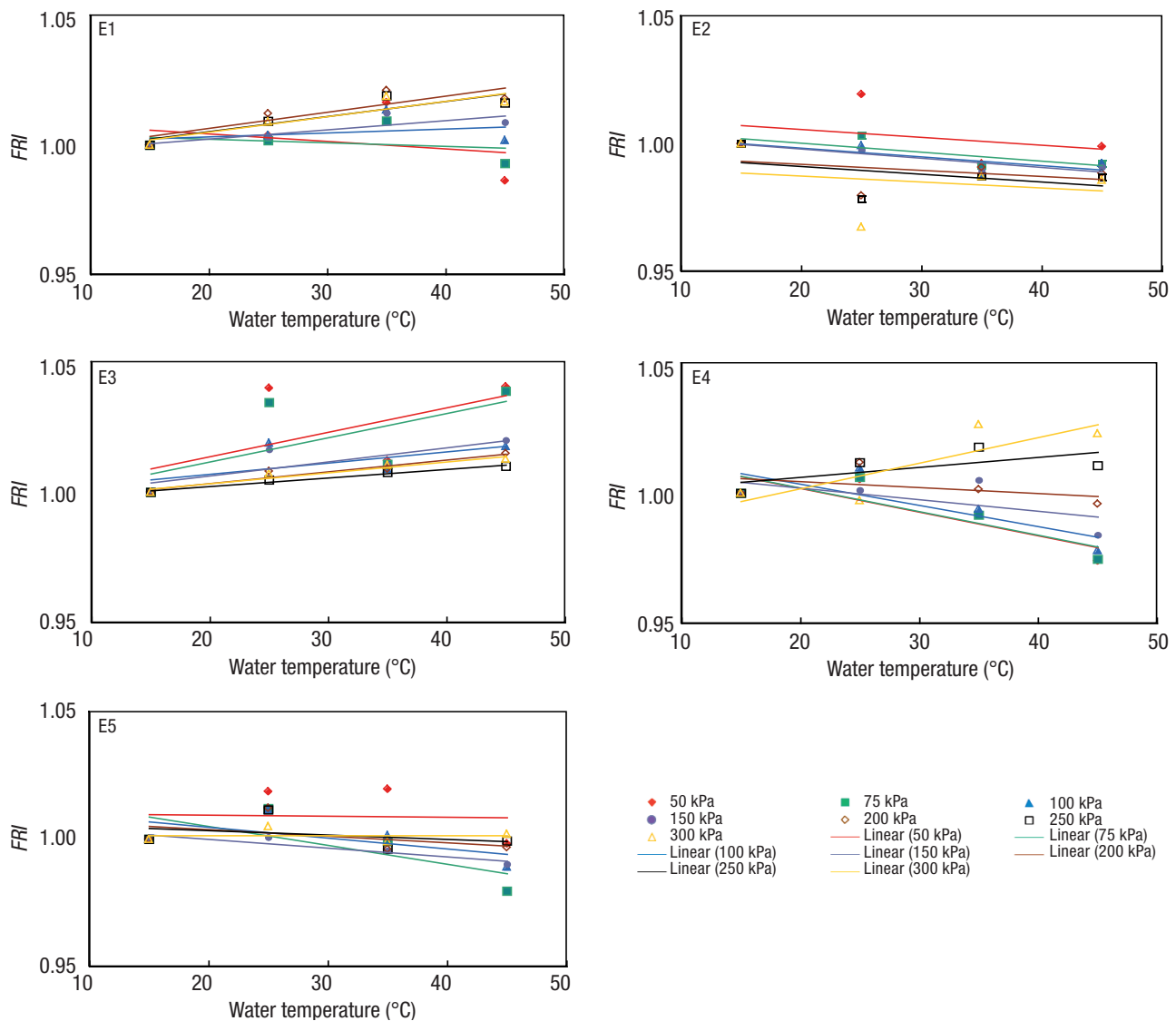


Figure 3. Flow rate index (*FRI*) and water temperature relations at various operating pressures for tested emitters.

Effect of water temperature on emitter discharges

The changes in the emitter's discharge values based on *FRI* resulting from the alternation of water temperatures at each operating pressure are shown in Fig. 3. The discharge measured at 15°C in the first test was taken as a reference. The figure illustrates the strong linear regression relationship between water temperature and the relative discharge rates of tested emitters at operating pressures ranging from 50 kPa to 300 kPa. The obtained result is in agreement with Zur & Tal (1981), Von Bernuth & Solomon (1986), and Dogan & Kirnak (2010). It is clear that the *FRI* values for non-compensating emitters were around one. This

means that the discharge rates change slightly with increasing water temperature where these emitters' x values were almost equal to 0.5 (fully turbulent). Therefore, any small discharge variation resulting from temperature changes should not be caused by the change of viscosity (Karmeli & Keller, 1975; Rodríguez-Sinobas *et al.*, 1999). The *FRI* values for compensating emitters, except E4, at operating pressures of 250 and 300 kPa decrease with increasing water temperature from 15°C to 45°C because they had x values around zero (Decroix & Malaval, 1985; Dogan & Kirnak, 2010). E4 and E5 discharges varied from +2.6% to -2.3% and from +2.0% to -0.2%, respectively, with increasing water

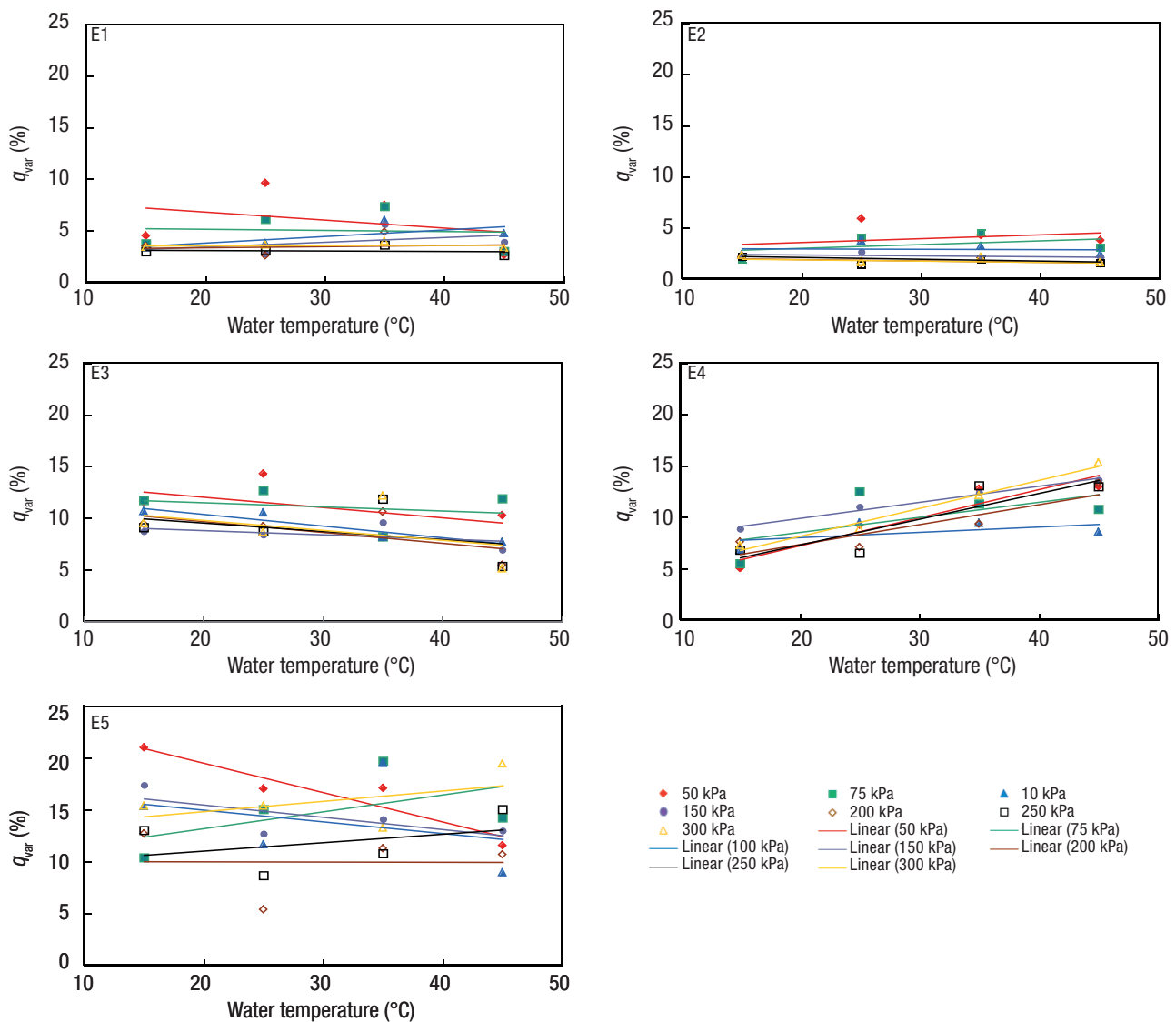


Figure 4. Effect of water temperature on emitter discharge rate variation (q_{var}) at various operating pressures for tested emitters.

temperature from 15°C to 45°C relative to the discharge rate at 15°C at test operating pressures. As operating pressure was increased, the effects of increased water temperature on emitter flow rate were insignificant ($p > 0.05$).

In Fig. 4, the values of q_{var} for E1 and E2 (non-compensating emitters) were lower than 5% at various test water temperatures and operating pressure ranges. The corresponding E3 fell between 5% and 10% with increasing water temperature from 15°C to 45°C at test operating pressures ranging from 150 kPa to 300 kPa. ASABE standards (ASABE, 2005) have shown that q_{var} for E1 and E2 fall within the excellent category. E3 was categorized as very good at all test operating

pressures and water temperatures, except with increasing water temperature from 15°C to 25°C at operating pressures ranging from 50 kPa to 100 kPa, which was categorized as fair.

On the other hand, values of q_{var} ranged from 5.03% to 12.5% and from 8.5% to 15.3% with increasing water temperature from 15°C to 25°C and from 35°C to 45°C, respectively, at all test operating pressures for E4. Therefore, the category of this emitter was neither very good nor fair based on the classification of ASABE, while values of E5 were almost from 10% to 20% with increasing water temperature and operating pressure, as shown in Fig. 4. However, E5 was considered as poor or fair emitter.

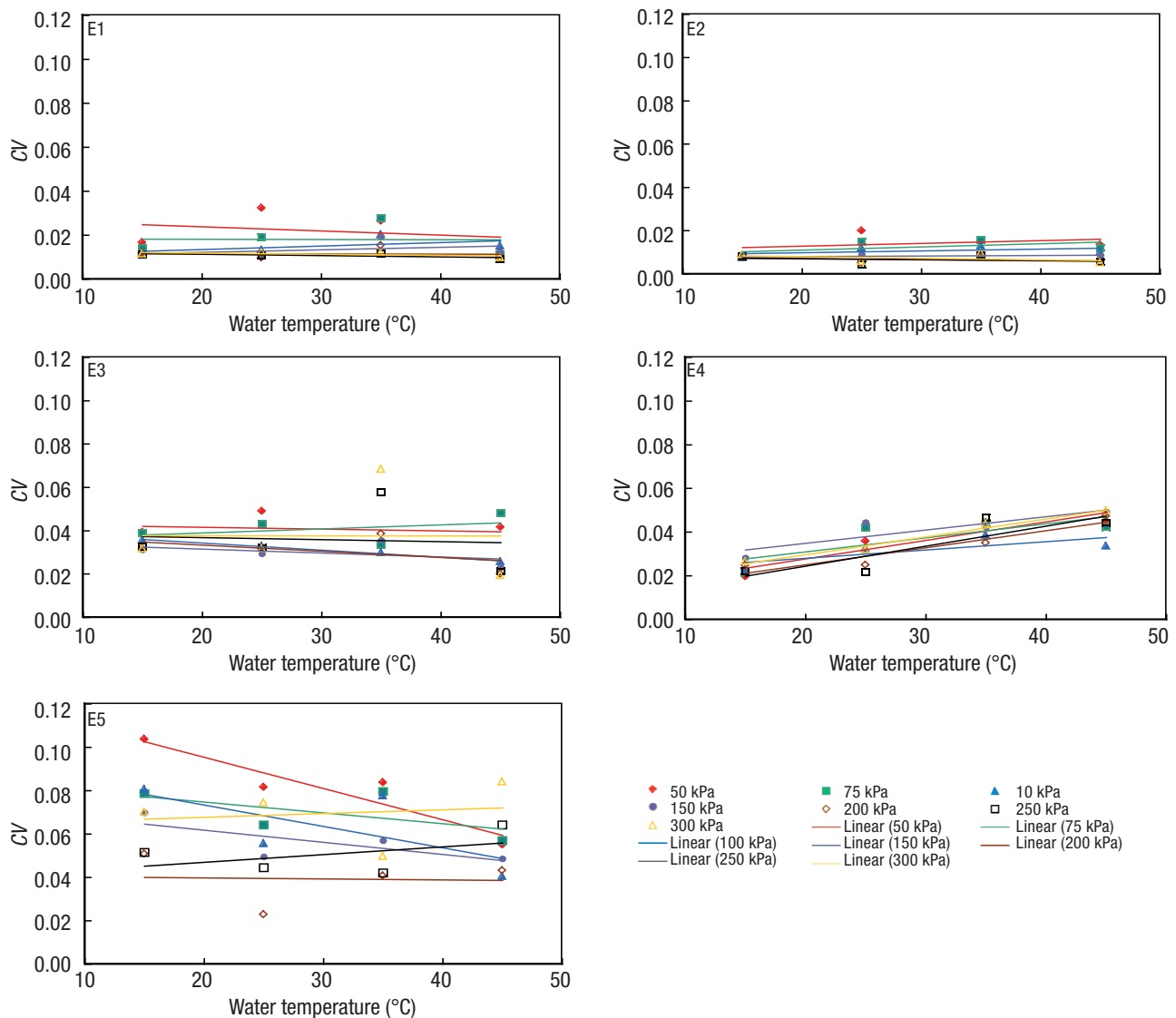


Figure 5. Effect of water temperature on manufacturer's coefficient of variation of emitters (CV) at various operating pressures for tested emitters.

Determination of hydraulic characteristics

Fig. 5 shows the CV values were found to be lower than 0.10 as water temperatures increase from 15°C to 45°C at test operating pressures ranging for E1, E2, and E3. On the other hand, average CV values of the E4 increased from 0.019 to 0.049, and the corresponding values of E5 emitter decreased from 0.10 to 0.023 with a water temperature increase from 15°C to 45°C (Fig. 5) at each test operating pressure. These emitters were classified as good emitters based on the classification of ASABE. Moreover, results indicated a non-significant ($p > 0.05$) effect of water temperature on CV values for

non-compensating and compensating emitters. The results were consistent with the findings of Clark *et al.* (2005) and Dogan & Kirnak (2010). Furthermore, results have shown that there was no obvious regular increase or decrease in CV values with increases in operating pressure for all tested emitters. The CV values of the non-compensating emitters were lower than those of compensating emitters. This is due to the difficulty of manufacturing the movable parts in the compensating emitters. This was in agreement with Özekici & Sneed (1995) and Özekici & Bozkurt (1999), except for the studies of Bralts *et al.* (1981), Madramootoo *et al.* (1988), and Hezarjaribi *et al.* (2008).

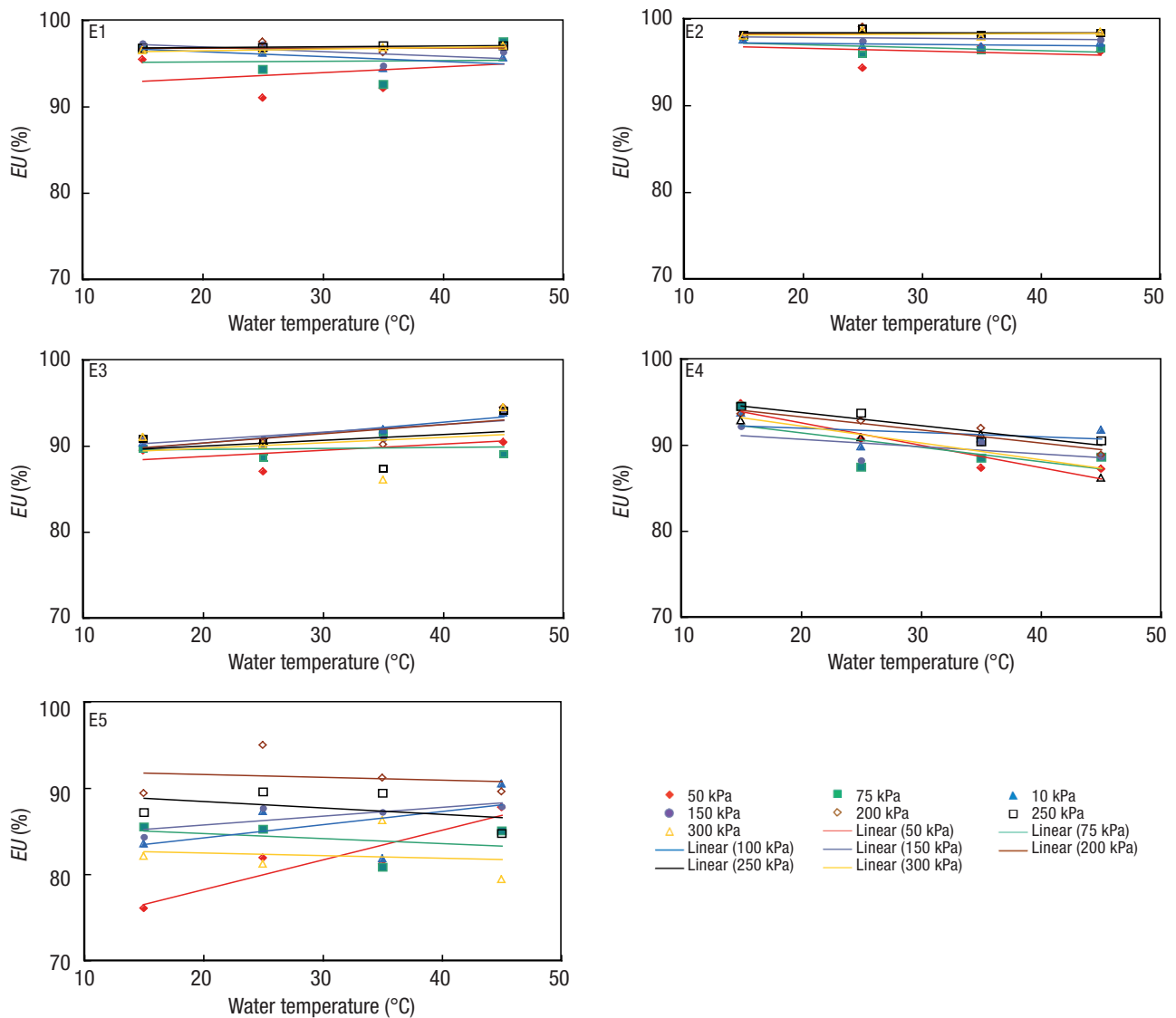


Figure 6. Effect of water temperature on emission uniformity (EU) at various operating pressures for tested emitters.

The results in Fig. 6 show that EU values were ranging from 91% to 97.5%, 94.3% to 99%, and 86% to 94.5% for E1, E2, and E3, respectively. These emitters increased with increasing operating pressure at water temperatures from 15°C to 45°C, while E4 and E5 had EU value averages of 90.8% and 85.7%, respectively, EU values of the E4 decreased with increasing test water temperatures ranging at each test operating pressure. The corresponding values of E5 showed no obvious regular increase or decrease in the values with increases in operating pressure and water temperature. It is clear from the statistical analysis of these values that there was an insignificant effect ($p > 0.05$) of water temperature, but operating pressure effect was signifi-

cant ($p < 0.01$). However, based on the classification of ASABE, the non-compensating emitters fall within the excellent category. As the E4 was neither an excellent nor good emitter based on water temperature, the E5 was rated as a good emitter.

To clarify, the parameters affecting the pressure difference at emitters should be maintained in a range such that the desired design EU is obtained. Eq. [6] consists of two terms; the first expresses the discharge rate variation resulting from CV , which is reduced by increasing the number of emitters per plant, and the second, q_{\min} / \bar{q} , expresses the discharge rate variation resulting from pressure variation and also the system application efficiency (Wu & Gitlin, 1975).

Table 3. Average q (emitter discharge rate), q_{var} (emitter discharge rate variation), CV (manufacturer's coefficient of variation of emitters), and EU (emission uniformity) of emitters under different operating pressures

Emitters code	50 kPa	75 kPa	100 kPa	150 kPa	200 kPa	250 kPa	300 kPa
Average q							
E1	3.071	3.658	4.163	5.015	5.769	6.465	7.096
E2	5.519	6.543	7.412	8.891	10.098	11.096	11.995
E3	2.163	2.609	2.960	3.577	4.099	4.563	4.974
E4	3.472	3.515	3.527	3.527	3.537	3.564	3.623
E5	4.587	4.609	4.623	4.599	4.611	4.662	4.702
Average q_{var}							
E1	6.04	5.04	4.45	3.90	3.48	3.05	3.56
E2	3.97	3.38	2.92	2.28	1.79	1.77	1.94
E3	11.05	11.12	9.24	8.40	8.65	8.75	8.83
E4	10.01	10.02	8.56	11.49	9.33	9.85	10.91
E5	16.70	14.87	13.89	14.31	10.01	11.88	15.88
Average CV							
E1	0.022	0.018	0.015	0.013	0.011	0.011	0.011
E2	0.014	0.013	0.011	0.008	0.007	0.007	0.007
E3	0.041	0.041	0.031	0.030	0.030	0.036	0.038
E4	0.036	0.037	0.032	0.041	0.033	0.034	0.038
E5	0.081	0.070	0.064	0.056	0.039	0.050	0.069
Average EU							
E1	94.0	95.3	95.8	96.4	96.8	97.0	96.7
E2	96.3	96.7	97.1	97.8	98.3	98.4	98.3
E3	89.5	89.7	91.6	91.7	91.5	90.7	90.4
E4	90.0	89.8	91.5	89.8	91.8	92.3	90.3
E5	81.7	84.2	85.8	86.8	91.3	87.7	82.2

This is mathematically expressed by using Eq. [1] as follows:

$$\frac{q_{\text{min}}}{\bar{q}} = \left(\frac{P_{\text{min}}}{P_a} \right)^x \quad [7]$$

where P_{min} is the minimum pressure, and P_a is the average or design pressure. Substituting Eq. [7] into Eq. [6] yields the following:

$$\frac{P_{\text{min}}}{P_a} = \left(\frac{EU}{1 - (1.27CV / \sqrt{n})} \right)^{1/x} \quad [8]$$

The following example demonstrates Eq. [8] with E3 and E4. When water temperature equals 35°C, E3 has $EU = 90\%$, $CV = 0.036$, $x = 0.473$, $P_a = 150$ kPa, and $n = 1$. Using Eq. [8], the allowable P_{min} is 135 kPa, which becomes the design limitation with chosen laterals. Similarly, E4 has $CV = 0.042$, $x = 0.025$, and the values of EU , P_a , and n still as in E3 at the same water temperature. The allowable P_{min} is 23 kPa. The

example illustrated that pressure variation P_{min} / P_a in a drip irrigation system (*i.e.*, the system application efficiency) is affected by the values of CV and x .

The influence of structural design parameters of an emitter on discharge rate and hydraulic performance

The studied inside structural parameters of the trapezoidal labyrinth emitter includes width (W) and length (L) of flow path, also trapezoidal unit (denotations) numbers (N), height (H), and spacing (S). Tables 1 and 3 make it evident that N and L have an inverse correlation with the discharge rate of the emitter. With the increase of W , H , and S , the non-compensating emitters' discharges decreased first and then increased later, while the compensating emitters' discharges decreased. The greater N and L are, the greater x is, which indicates that the emitter discharge is

Table 4. Standard error (*SE*) of regression coefficients and probability (*p* value) of structural parameters, operating pressure (*P*) and water temperature (*T_w*) for regression *q*, *q_{var}*, *CV* and *EU* models

Dependent variable		Independent variables						
		<i>N</i>	<i>L</i>	<i>W</i>	<i>H</i>	<i>S</i>	<i>P</i>	<i>T_w</i>
<i>q</i>	<i>SE</i>	±0.33	±0.44	±0.11 × 10 ³	±0.30 × 10 ²	±0.10 × 10 ³	±0.08 × 10 ⁻²	±6.56 × 10 ⁻³
	<i>p</i> value	3.05 × 10 ⁻²⁴	1.12 × 10 ⁻²³	1.15 × 10 ⁻²³	4.82 × 10 ⁻²⁴	8.64 × 10 ⁻²⁴	1.79 × 10 ⁻²⁴	9.69 × 10 ⁻¹
<i>q_{var}</i>	<i>SE</i>	±0.94	±1.22	±0.31 × 10 ³	±0.83 × 10 ²	±0.29 × 10 ³	±2.37 × 10 ⁻³	±1.83 × 10 ⁻²
	<i>p</i> value	1.77 × 10 ⁻⁴	1.50 × 10 ⁻⁴	8.95 × 10 ⁻⁵	1.89 × 10 ⁻⁴	1.26 × 10 ⁻⁴	6.40 × 10 ⁻³	3.14 × 10 ⁻¹
<i>CV</i>	<i>SE</i>	±0.42 × 10 ⁻²	±0.54 × 10 ⁻²	±1.36	±0.36	±1.28	±1.04 × 10 ⁻⁵	±8.06 × 10 ⁻⁵
	<i>p</i> value	6.33 × 10 ⁻⁹	5.35 × 10 ⁻⁹	2.56 × 10 ⁻⁹	6.92 × 10 ⁻⁹	4.03 × 10 ⁻⁹	4.72 × 10 ⁻³	6.24 × 10 ⁻¹
<i>EU</i>	<i>SE</i>	±0.96	±1.25	±31.41 × 10 ²	±0.84 × 10 ²	±2.96 × 10 ²	±2.41 × 10 ⁻³	±18.63 × 10 ⁻³
	<i>p</i> value	2.95 × 10 ⁻⁴⁷	1.55 × 10 ⁻⁴⁴	1.57 × 10 ⁻⁴⁵	4.05 × 10 ⁻⁴⁵	3.44 × 10 ⁻⁴⁵	5.12 × 10 ⁻³	7.42 × 10 ⁻¹

more sensitive to the variation of the pressure (Tables 1 and 2). For compensating emitters, E4 with *N* = 22, *x* value was 0.018, while the *x* value for E5 with *N* = 12 was 0.011. The corresponding values for non-compensating emitters were 0.44 and 0.47 for E2 (*N* = 22) and E1 (*N* = 61), respectively. On the contrary, *W*, *H*, and *S* have an inverse correlation with *x* values for non-compensating emitters, but the correlation is positive for compensating emitters.

In Tables 1 and 3, it is obvious that the *N*, *L*, *W*, *H*, or *S* inside the emitter have an impact on emitter hydraulic performance characteristics. The general trend is that as the *N* or *L* increase, the hydraulic performance of the emitter is improved. For instance, average *q_{var}* value of E1 with *N* = 61 is less (4.22%) as compared to E5 (13.93%) with *N* = 12. The same trend applies for the coefficient of manufacturing variation; for E1, *CV* = 0.015, as compared to *CV* = 0.061 for E5. The same effect also was noticed for the *EU*; E1 variation was 96% as compared to 85.7% for E5. The above results are in agreement with Wei *et al.* (2007).

Mathematical regression model

Regression analysis is most often used for prediction. The goal in regression analysis is to create a mathematical model that can be used to predict the values of a dependent variable based upon the values of an independent variable. *MLR* models were developed for hydraulic performance criteria based on 140 measurements in the laboratory. *SE* of regression coefficients and probability of independent variables

have been presented in Table 4. Resulted models for computation of discharge emitter, emitter flow variation, and coefficient of manufacturing variation are presented in Eqs. [9]-[12], respectively, as follows:

For emitter discharge rate (*q*):

$$q = 4.24N + 5.40L + (1.36 \cdot 10^3)W + (3.69 \cdot 10^2)H - (1.28 \cdot 10^3)S + (1.07 \cdot 10^{-2})P - (0.26 \cdot 10^{-3})T_w \quad [9]$$

This developed model is significant with values for *R*² of 0.977. Table 4 reveals that all variables in the regression equation are highly significantly affected (*p* < 0.001) except *T_w* (water temperature), which was not significantly affected (*p* > 0.05). The ranking of significance was in the descending order as follows: *S*, *H*, *N*, *P*, *W*, and *L*.

For emitter flow variation (*q_{var}*):

$$q_{var} = 3.64N + 4.78L + (1.25 \cdot 10^3)W + (3.18 \cdot 10^2)H - (1.15 \cdot 10^3)S - (6.6 \cdot 10^{-3})P + (1.84 \cdot 10^{-2})T_w \quad [10]$$

This developed model has an *R*² of 0.936. All variables in the regression equation are highly significantly affected (*p* < 0.001) except *P*, which is very significant at 0.001 < *p* < 0.05. The *T_w* was not significantly affected (*p* > 0.05). The ranking of significance was in descending order as follows: *W*, *H*, *N*, *L*, *S*, and *P*.

For manufacturer’s coefficient of variation of emitters (*CV*):

$$CV = (2.58 \cdot 10^{-2})N + (3.37 \cdot 10^{-2})L + 8.68W + 2.26H - 8.05S - (3.00 \cdot 10^{-5})P + (3.95 \cdot 10^{-5})T_w \quad [11]$$

This developed model has an *R*² of 0.925. All variables in the regression equation are highly signifi-

cant ($p < 0.001$) except P , which is very significant at $0.001 < p < 0.05$. Also, the T_w was not significantly affected ($p > 0.05$). The ranking of significance was in descending order as follows: N , H , L , S , W , and P .

For emission uniformity, EU :

$$EU = 21.67N + 26.47L + (68.15 \cdot 10^2)W + (18.11 \cdot 10^2)H - (63.64 \cdot 10^2)S + (6.86 \cdot 10^{-3})P - (6.14 \cdot 10^{-3})T_w \quad [12]$$

This above model has the highest R^2 of 0.999. All variables in the regression equation are highly significant ($p < 0.001$) except P , which is very significant at $0.001 < p < 0.05$. The T_w was not significantly affected ($p > 0.05$). The ranking of significance was in descending order as follows: N , H , S , W , L , and P .

According to previous results shown in Table 4, the N and H are influential variables in the calculation of q , q_{var} , CV , and EU . Moreover, the regression coefficients of N and H are very sensitive. Since the SE of the coefficients of these variables are ± 0.33 ; ± 0.94 ; $\pm 0.42 \times 10^{-2}$, ± 0.96 and $\pm 0.30 \times 10^2$; $\pm 0.83 \times 10^2$; ± 0.36 , $\pm 0.84 \times 10^2$ for q , q_{var} , CV , and EU models, respectively. In contrast, the T_w is inoperative variable (the p value is high, suggesting that the null hypothesis of the slope being equal to zero is true) in all proposed models. This is confirmed by the values of SE of the regression coefficients for T_w variable.

As conclusions, the results have shown that the effects of increased water temperature (T_w) on emitter discharge rate were insignificant. Similarly, there was no significant effect of water temperature on emitter flow variation (q_{var}), manufacturer's coefficient of variation of emitters (CV), and emission uniformity (EU) values for non-compensating and compensating emitters. As for the effect of structural parameters of labyrinth emitters on hydraulic performance, the width (W) and length (L) of flow path, trapezoidal unit (dentations) numbers (N), height (H), and spacing (S) have a positive correlation with the hydraulic performance of the emitter, especially N and H variables which are very important. The result of this investigation may provide a basis for improving structural design for better performance of labyrinth emitters.

Acknowledgements

The authors would like to acknowledge Prince Sultan Research Institute and PSIPW research chair for sponsoring this research project.

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