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Discharge sensitivity of collapsible drip tapes to water temperature¹

Sensibilidade da vazão de fitas gotejadoras colapsáveis à temperatura da água

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HIGHLIGHTS:

The effect of water temperature variations on the discharge of collapsible thin-walled drip tapes was evaluated.

The emitter discharge sensitivity to water temperature is related to the flow exponent value of the emitter.

The emitter discharge sensitivity to water temperature was not significantly affected by the wall thickness of the drip tape.

ABSTRACT: The objective of this study was to quantify the effect of water temperature variations on the discharge of collapsible thin-walled drip tapes with integrated non-pressure-compensating emitters. The tests were conducted in the laboratory using an automated test bench. Tests were performed to determine the discharge-pressure curves by varying the water temperature from 20 to 50 °C. Nine emitter models of three wall thicknesses (6, 8, and 9 MIL) were evaluated. The coefficients K and x of the discharge-pressure curves varied according to the water temperature. In flat emitters of turbulent flow ($x < 0.5$), the discharge decreased as the temperature increased. In the welded emitters of turbulent flow, several responses were observed. Regarding emitter D ($x > 0.5$), the discharge increased as the temperature was increased, while for emitter C ($x < 0.5$), the discharge decreased; the highest discharge variations occurred at pressures higher than 60 kPa. For embossed emitters, the discharge increased as a function of temperature, however, the greatest variation occurred at the lowest pressures. None of the emitters showed significant difference in the discharge variation due to wall thicknesses.

Key words: emitter, turbulent flow, drip irrigation, water temperature

RESUMO: Objetivou-se neste estudo quantificar o efeito de variações da temperatura da água na vazão de fitas gotejadoras colapsáveis, de parede fina, com emissores integrados não regulados. Os ensaios foram conduzidos em laboratório utilizando estrutura de ensaios automatizada. Foram realizados ensaios para determinação das curvas vazão-pressão sob temperaturas de ensaio na faixa de 20 a 50 °C, para nove modelos de emissores com três espessuras de parede (6, 8 e 9 MIL). Curvas vazão-pressão apresentaram distintos parâmetros K e x para cada temperatura. Para os emissores planos de fluxo turbulento ($x < 0,5$), a vazão diminuiu com o incremento da temperatura. Para os emissores contínuos de fluxo turbulento, respostas diferentes foram obtidas, sendo que no emissor D ($x > 0,5$) a vazão aumentou com o incremento da temperatura, enquanto no emissor C ($x < 0,5$), a vazão diminuiu e as maiores variações de vazão ocorreram a partir de 60 kPa. Para o emissor moldado, a vazão aumentou em função da temperatura, porém, a maior variação ocorreu nas menores pressões. Para nenhum dos emissores houve diferença significativa na variação de vazão entre as espessuras de parede.

Palavras-chave: emissor, fluxo turbulento, gotejamento, temperatura da água

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INTRODUCTION

The use of collapsible drip tapes with integrated emitters in the irrigation of short-cycle crops, specifically vegetables, has gained market share owing to their satisfactory performance and low cost (Melo et al., 2019). The emitter is a key component in drip irrigation systems (Zhengying et al., 2012), and its operational and performance characteristics can be influenced by imperfections in the manufacturing process, variations in the operating pressure, clogging problems, and fluctuations in the water temperature.

The emitter discharge sensitivity to water temperature variations is influenced by the type of emitter. Minor discharge variations are usually observed in non-pressure compensating (NPC) emitters because of fluctuations in water temperature. Rodríguez-Sinobas et al. (1999) reported variation of less than 1.5% in the discharge of emitters, with water temperatures ranging from 20 to 40 °C. Al-Amoud et al. (2014) found no significant variation in the discharge of NPC emitters operated with water temperatures varying from 15 to 45 °C. Senyigit et al. (2012) observed that the emitter discharge tends to increase with the increase in water temperature (20 to 40 °C); however, under operating pressures between 90 and 120 kPa, there was no significant difference in the discharge variation.

In a more recent study, Senyigit & Ilkhan (2017) found increase of approximately 5% in the discharge of NPC emitters due to the increase in water temperature (from 20 to 50 °C). However, Clark et al. (2005) analyzed two models of thin-walled drip tapes with integrated NPC emitters and observed discharge variations of up to 97%, indicating that this type of material is more sensitive to water temperature when compared to thicker wall tubes used in the other studies previously indicated. This may be predominantly associated with the

properties of the material that constitutes the drip tapes and not due to the viscosity variations of water because all the emitters studied operated under turbulent flow conditions.

This study aims to quantify the effect of water temperature variations on the discharge of thin-walled collapsible drip tapes with integrated non-pressure compensating emitters.

MATERIAL AND METHODS

The experiment was conducted at the Irrigation Testing Laboratory, Department of Biosystems Engineering, College of Agriculture Luiz de Queiroz - ESALQ/USP. An automated test bench operated as a hydraulically closed circuit (Figure 1) was used. The test bench was equipped with a data acquisition and control system based on a microcontroller module (Rocha et al., 2017). A supervisory application with a graphical user interface was used to configure, monitor, and record test conditions.

The bench was designed to allow simultaneous evaluation of 25 emitters to comply with the operational testing requirements indicated in ABNT (2006). The 300 L water tank was coated with double Styrofoam plates to provide thermal insulation.

The water heating system consisted of a three-phase 220V electrical resistance, triggered by a contactor and a digital thermostat configured for on/off control with a tolerance of 0.5 °C near the target temperature. The water cooling system in the tank was used only for the test temperature of 20 ± 1 °C and had no automated action. The target temperature was achieved and maintained only with the manual addition of filtered ice in the tank. The water temperature at the inlet of each of the 25 drip tape segments was monitored by DS18B20 sensors (Maxim, 2018), with a measurement uncertainty of 0.5 °C and measurement range of -10 to 85 °C.

The pressure control system consisted of a pump equipped with a variable frequency drive and a proportional-integral-

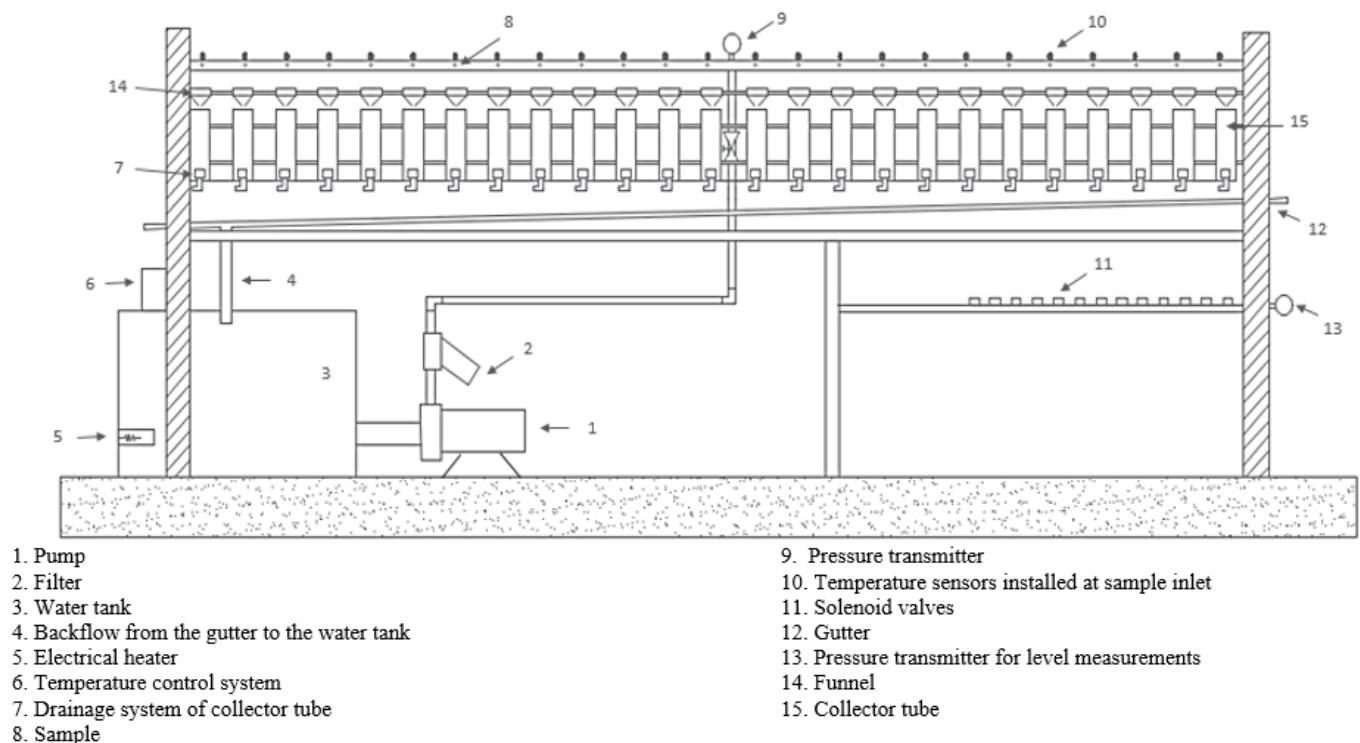


Figure 1. Test bench

derivative controller (PID), which aimed to ensure accuracy and stability for the control of test pressures (Bombardelli et al., 2019; Rocha et al., 2017). A pressure transmitter was used; it had a measurement range of 0 to 500 kPa, resolution of 0.1 kPa, and expanded measurement uncertainty of 0.1% in relation to the full scale (FS).

The discharge determination of each emitter was performed automatically by measuring the variation of the water level in the collector tubes positioned under each of the emitters. The collector tubes were cylindrical, with a nominal diameter of 50 mm and height of approximately 1 m. The level variation in each collector tube in a given time interval can be converted into a volume of collected water and consequently, the discharge can be determined. The final and initial levels were monitored by a pressure transmitter with a measuring range from 0 to 10 kPa, resolution of 0.001 kPa, and expanded uncertainty of 0.05% FS. A solenoid valve was installed at the base of each collector tube to enable drainage of the collector after each discharge determination routine.

Drip tapes with wall thicknesses of 6, 8, and 9 MIL (0.150, 0.200, and 0.225 mm, respectively) were evaluated, with the following three types of emitters: flat (A and B), welded (C and D), and molded or embossed (E). The specifications for each model are listed in Table 1.

For each sample, the discharge-pressure curves (Eq. 1) were determined at the reference temperature (23 °C), following the recommendations of the ABNT standard (2006) and at four water temperatures (20, 30, 40, and 50 °C). Twenty-five segments of drip tapes were randomly obtained from a single coil. The segments had a length of approximately 50 cm. The samples were subjected to pressures ranging from 20 to 100 kPa with increments of 20 kPa.

$$q = K H^x \quad (1)$$

where:

- q - emitter discharge, L h⁻¹;
- H - pressure head, m;
- x - flow exponent; and,
- K - coefficient that depends on the nominal discharge of the emitter.

To estimate the temperature discharge index (i_T) of the emitters at each temperature and pressure, the ratio between

the discharge at the target temperature and the discharge at the reference temperature (Eq. 2) was calculated, as recommended by the ASABE standard (2017).

$$i_T = \frac{q_i}{q_{ref}} \quad (2)$$

where:

- i_T - temperature discharge index;
- q_i - emitter discharge at temperature i , L h⁻¹; and,
- q_{ref} - emitter discharge at reference temperature, L h⁻¹.

To test the significance of the models fitted to the data, variance analysis and F test were used at $p \leq 0.05$.

RESULTS AND DISCUSSION

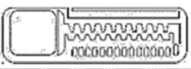

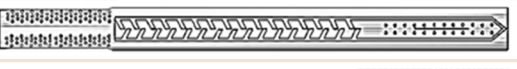



Figure 2 presents the discharge-pressure curves of the nine models of drip tapes evaluated at five water temperatures.

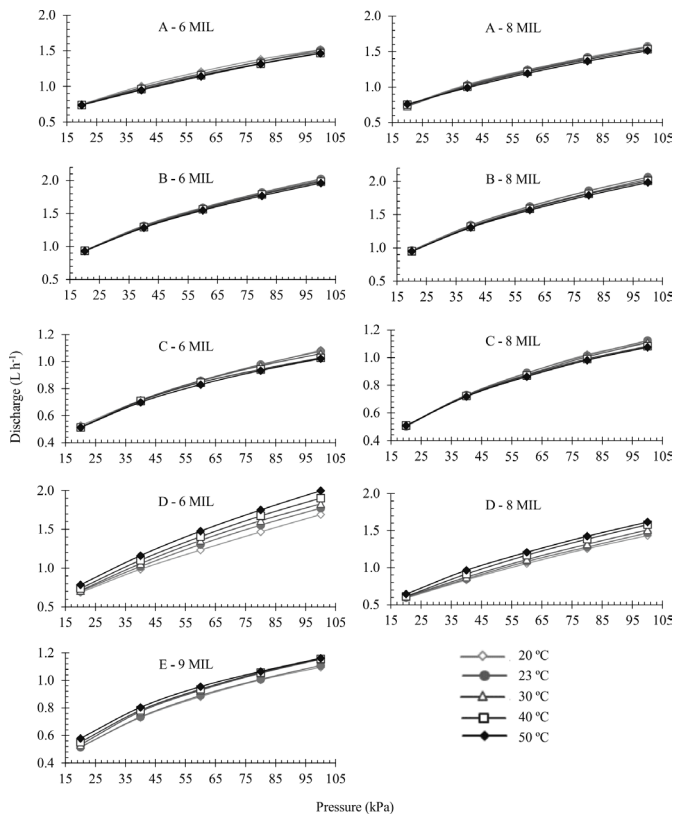
The discharge-pressure curves of the turbulent flow flat emitters (models A and B) indicate low sensitivity of the emitter discharge to water temperature. The highest discharge variations relative to the reference discharge at 23 °C for both emitters were observed at 50 °C under an operating pressure of 100 kPa. Emitter A presented discharge reductions of 4.1 and 4.0% for drip tapes of 6 and 8 MIL wall thickness, respectively. For emitter B, the discharge decreased by 3.0% for the drip tapes of 6 MIL wall thickness and 3.8% for the 8 MIL. The decrease in the mean discharge as a function of water temperature was not statistically significant ($p > 0.05$) in any of the test pressures or wall thicknesses.

The small discharge decreases were assumed to be caused by the effects of water temperature on the characteristics of vortex formation in the deflectors of the emitter labyrinths; therefore, the increase in water temperature may have caused increased energy dissipation by the vortexes and consequent reduction in the emitter discharge. Vortex formation is an efficient mechanism for energy dissipation that plays a significant role in controlling the discharge of turbulent flow emitters (Oliveira et al., 2020).

For model C (welded turbulent flow emitter), the discharge-pressure curves in the range of 20 to 40 kPa overlapped,

Table 1. General characteristics of the emitters evaluated (q_n - Nominal discharge; P - Nominal pressure; E - Wall thickness; ID - Identification; MIL - Thousandth of an inch)

Design	ID	Manufacturer	Model	q_n (L h ⁻¹)	P (kPa)	E (mm ; MIL)
	A	Netafim	Stream line	1.60	100	0.150 ; 6
	B	NaanDanjain	Turbo Excel	2.00	70	0.150 ; 6
	C	NaanDanjain	Turbo Tape	2.00	90	0.200 ; 8
	D	Golden Tree	Silver Drip	1.13	70	0.150 ; 6
	D	Golden Tree	Silver Drip	1.13	100	0.200 ; 8
	E	Rain Bird	Raintape	1.70	70	0.150 ; 6
				1.44	100	0.200 ; 8
				1.00	55	0.225 ; 9



See Table 1 for description of emitter types A, B, C, D, and E; MIL - Thousandth of an inch; Flat emitters (A and B); Welded emitters (C and D); Embossed emitters (E)

Figure 2. Discharge as a function of pressure in emitters with different wall thicknesses at five water temperatures

indicating that there was no effect of water temperature on the discharge-pressure curve of this emitter. This was confirmed by the statistical test of means, in which the discharge variation as a function of temperature for this pressure interval was insignificant ($p > 0.05$). At pressures higher than 40 kPa, the curves for both wall thicknesses were distanced, and the response of the emitter discharge to the pressure decreased as the temperature was increased. Thus, the combined effect of water temperature and pressure was more evident, specifically for the tape with 6 MIL wall thickness. Within the range of 60-100 kPa, the difference between the means at different temperatures was statistically significant ($p \leq 0.05$). The highest discharge variations were observed at a temperature of 50 °C and operating pressure of 100 kPa, with a decrease of 4.4% for the tape of 6 MIL wall thickness and 5.6% for the 8 MIL wall thickness model. However, the discharge variation was not statistically significant when the wall thicknesses were compared.

Emitter D presented an apparent difference between the discharge-pressure curves at the studied temperatures. At an operating pressure of 40 kPa, significant differences were observed ($p \leq 0.05$) between the means for both wall thicknesses. Similar to the other emitters indicated above, the highest discharge variations occurred in the highest values of temperature and pressure; however, with a tendency to increase the discharge with the temperature with observed values of 12.3 and 9.9% for the tapes with 6 and 8 MIL wall thicknesses, respectively.

For emitter E, the discharge-pressure curves at temperatures of 23 and 20 °C overlapped, as well as the curves at 30 and

40 °C, indicating no discharge variation within this range of temperatures. However, a significant variation ($p \leq 0.05$) was observed between the curves at the reference and highest temperatures. The greatest variations occurred at the lowest pressures. The discharge variation decreased with increasing water temperature and pressure. The flow exponent for this emitter presented a value of up to 0.467, but the discharge tended to increase with an increase in water temperature, where the highest discharge variation was 12.1% at a temperature of 50 °C and operating pressure of 20 kPa, which varies from the other emitters studied. The tendency to increase the discharge with the temperature for emitter E may be associated with the physical characteristics of this drip tape, which is composed of a twin-wall, where a water flow passage chamber is formed. Inside this chamber, the lower (smooth) and upper walls (which contain the labyrinth) remain less compressed at lower pressures. Thus, for lower pressures, the water passage section is larger, resulting in lower head loss and higher discharge.

Table 2 presents the coefficients of the discharge-pressure equations and the coefficients of discharge variation due to manufacturing (CV_p) for the emitters evaluated at the five water temperatures. There were minor changes in the values of the proportionality coefficient (K) and in the flow exponent (x) as a function of variations in water temperature. According to Bralts et al. (1981), the K coefficient factors are relative to the construction of the emitter and thus, the variations due to manufacturing would be embedded in the value of K . The factors inherent to the flow behavior are expressed by the flow exponent (x). The K and x coefficients were statistically significant ($p \leq 0.05$) for all cases presented in Table 2.

The values of the flow exponents for both flat emitters (models A and B) were less than 0.5, with maximum values of 0.471 for emitter A and 0.486 for emitter B. According to Keller & Karmeli (1974), an emitter is characterized as having full turbulent flow when the flow exponent has values equal to 0.5. The higher the exponent flow, the greater the discharge sensitivity to variations in operating pressure and fluctuations in water temperature. Upon evaluating NPC emitters with flow exponents between 0.434 and 0.491, Zhangzhong et al. (2015) reported that the area of the vortex regions became more developed with an increase in operating pressure, reducing the width of the main flow region of the labyrinth, and reducing the sensitivity of the discharge to the operating pressure.

For model C, the flow exponents were also less than 0.5, with maximum values of 0.457 and 0.491 for wall thicknesses of 6 and 8 MIL, respectively. This result indicates that the labyrinth of emitter C also has vortex areas, which would justify reducing the discharge due to temperature variations. However, its constructive and dimensional characteristics are significantly different from those of flat emitters because they are made of a more elastic material with a larger area of contact between its wall and water. The effect of temperature combined with pressure may cause greater discharge variations, specifically at higher pressures.

For model D, the values of the flow exponent were greater than 0.5, with values up to 0.591 and 0.599 for tapes with wall thicknesses of 6 and 8 MIL, respectively. According to Keller &

Table 2. Hydraulic characteristics of the evaluated emitters at five water temperatures

Model	T (°C)	K	x	CV _f (%)	Model	T (°C)	K	x	CV _f (%)
A 6 MIL	20	0.198	0.442	2.7	A 8 MIL	20	0.184	0.466	2.2
	23	0.188	0.451	2.8		23	0.184	0.467	2.2
	30	0.198	0.437	3.3		30	0.178	0.471	2.7
	40	0.196	0.435	3.1		40	0.194	0.449	2.7
	50	0.178	0.457	2.9		50	0.196	0.443	2.5
B 6 MIL	20	0.231	0.470	1.7	B 8 MIL	20	0.236	0.471	1.2
	23	0.228	0.474	1.6		23	0.235	0.472	1.1
	30	0.214	0.486	1.6		30	0.230	0.473	1.2
	40	0.233	0.465	1.6		40	0.238	0.463	1.0
	50	0.231	0.463	1.7		50	0.241	0.457	1.1
C 6 MIL	20	0.133	0.454	2.8	C 8 MIL	20	0.121	0.482	2.4
	23	0.131	0.457	2.7		23	0.117	0.491	2.6
	30	0.137	0.445	2.5		30	0.124	0.476	2.2
	40	0.147	0.422	2.5		40	0.131	0.459	2.0
	50	0.142	0.422	2.4		50	0.131	0.458	2.8
D 6 MIL	20	0.121	0.571	2.6	D 8 MIL	20	0.109	0.558	2.7
	23	0.118	0.586	2.5		23	0.105	0.571	2.9
	30	0.120	0.591	2.9		30	0.104	0.577	2.8
	40	0.124	0.591	2.5		40	0.103	0.591	3.3
	50	0.134	0.585	2.3		50	0.103	0.599	2.5
E 9 MIL	20	0.113	0.463	2.1					
	23	0.129	0.467	2.3					
	30	0.135	0.467	2.0					
	40	0.145	0.451	1.9					
	50	0.166	0.423	1.6					

See Table 1 for description of emitter types A, B, C, D, and E; K - Coefficient of proportionality of the discharge-pressure equation; x - Flow exponent; CV_f - Coefficient of variation due to manufacturing effects; MIL - Thousandth of an inch

Karmeli (1974), the emitter is characterized as having partial turbulent flow for these flow exponent values, and therefore the discharge presents greater sensitivity to water pressure and temperature. In addition to the discharge variation with water temperature, a significant difference ($p \leq 0.05$) in discharge between the wall thicknesses of the tapes at the reference temperature was also observed. The discharge of model D of 6 MIL wall thickness was 20.54% higher than that of model D of 8 MIL (operating at 100 kPa). However, this discharge variation among wall thicknesses is also reported by the manufacturer, with a value of approximately 18.05%. Similar to the flat emitters, model E presented flow exponents lower than 0.5.

For all evaluated models, CV_f values were lower than 7%, which complies with the requirements of the ABNT standard (2006) regarding discharge variability due to manufacturing effects. In accordance with previous investigations (Al-Amoud et al., 2014; Clark et al., 2005; Dogan & Kirnak, 2010; Rodríguez-Sinobas et al., 1999; Senyigit & Ilkhan, 2017), no specific trend was found regarding CV_f and variations in water temperature.

Figure 3 presents the temperature discharge index (i_T) values as a function of water temperature for the evaluated emitter models. The i_T refers to the ratio between the discharge at a given temperature (q_i) and the discharge at a reference temperature (q_{ref}); therefore, when the i_T value is closer to 1, the discharge variation as a function of water temperature is lower. Values above 1 indicate that the variation due to water temperature increases; that is, the higher the thermal increment, the higher the emitter discharge. Values of i_T lower than 1 indicate that the discharge of a given emitter decreases when the water temperature increases.

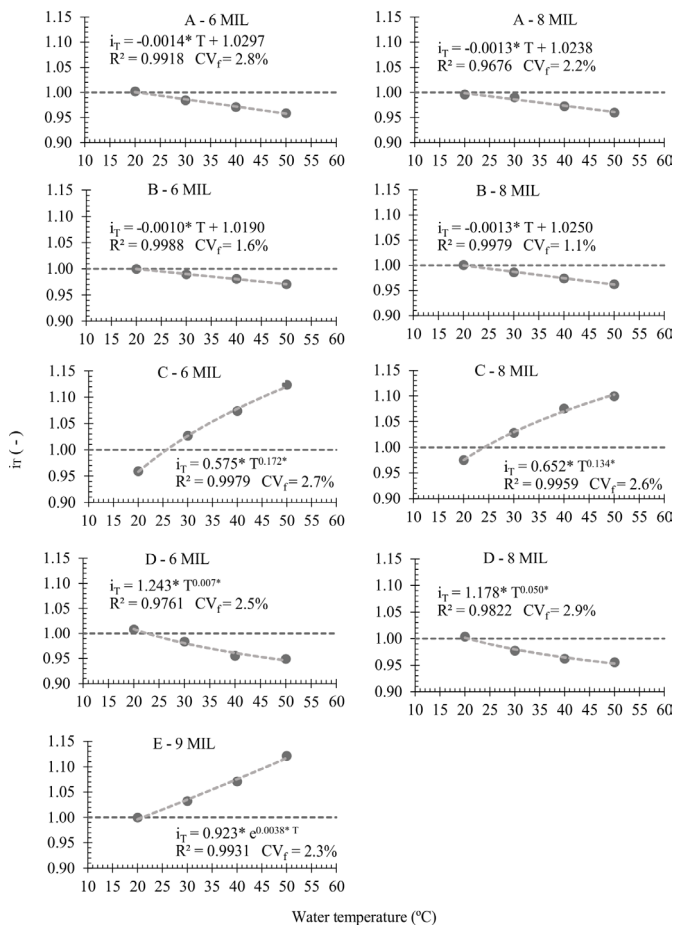
In general, the i_T values present linear variation as a function of water temperature in the flat emitters of turbulent

flow (models A and B), in accordance with previous studies (Al-Amoud et al., 2014; Dogan & Kirnak, 2010; Parchomchuk, 1976; Senyigit & Ilkhan, 2017; Zur & Tal, 1981). For welded turbulent flow emitters (models C and D), the best fitting of i_T according to the water temperature was found to be a power-law model. For the embossed emitter (model E), the best fit was an exponential model.

Clark et al. (2005) reported that linear relationships between i_T and water temperature indicate the behavior of more rigid emitters, where the effect of material elasticity is irrelevant. For welded emitters, specifically for those coupled to thinner wall tapes, greater elasticity of the material tends to contribute to a quadratic relationship between discharge variation and water temperature. For some models, the trend of discharge variation as a function of temperature is ascending; in other types of emitters, this relationship is decreasing.

The variations in i_T as a function of water temperature are related to the value of the emitter flow exponent (Decroix & Malaval, 1985; Rodríguez-Sinobas et al., 1999). For $x < 0.5$, there was a decrease in discharge as the temperature was increased; for $x = 0.5$, there was no variation in the discharge due to water temperature; for $x > 0.5$, there was an increase in discharge in response to the increase in temperature. The data obtained in this study presents results similar to those reported in previous literature.

Figure 4A presents the distribution of i_T values determined in various studies as a function of the emitter flow exponent (Rodríguez-Sinobas et al., 1999; Senyigit & Ilkhan, 2017; Zur & Tal, 1981) and the values observed in this study relative to the experimental adjustment proposed by Decroix & Malaval (1985). The correlation between the observed data and the adjustment presented values of the mean absolute error EMA = 0.021. The distribution of i_T values obtained by the theoretical



See Table 1 for description of emitter types A, B, C, D, and E; MIL - Thousandth of an inch; CV_f - Coefficient of variation due to manufacturing effects for water at 23 °C; R^2 - Coefficient of determination; * - Significant at $p \leq 0.05$ by F test

Figure 3. Temperature discharge index (i_T) as a function of the water temperature under operating pressure of 100 kPa for emitters A, B, C, D, and 20 kPa for the emitter (E)

model proposed by Rodríguez-Sinobas et al. (1999) (Figure 4B) and the observed data (Figure 4A) presented a better correlation ($EMA = 0.014$). This result indicates that the variations in i_T for the emitters used in this study occurred mainly due to the effect of water viscosity. The material composition did not significantly influence the discharge sensitivity of the emitters, unlike the results found by Clark et al. (2005). Figure 4B presents the distribution of the data by the same authors and the data observed in this study, in relation to the theoretical adjustment.

Relative to the proposal by Decroix & Malaval (1985), the theoretical model presents a better fit to the observed data, which is confirmed by the values of Root Mean Square Error (RMSE) and Pearson's correlation coefficient. This response implies that the variations in the emitters used in this study occur mainly because of water viscosity effects.

Some studies (Dogan & Kirnak, 2010; Senyigit & Ilkhan, 2017) defining the standard response or turbulent flow emitters indicate that the increase in discharge is associated with the increase in water temperature; however, this response would be associated only with emitters that have flow exponents greater than 0.5. Commercial emitters present a range of flow exponent values, some with exponents smaller than 0.5, and some with larger exponents; however, all are considered turbulent flow emitters, resulting in different discharge responses by

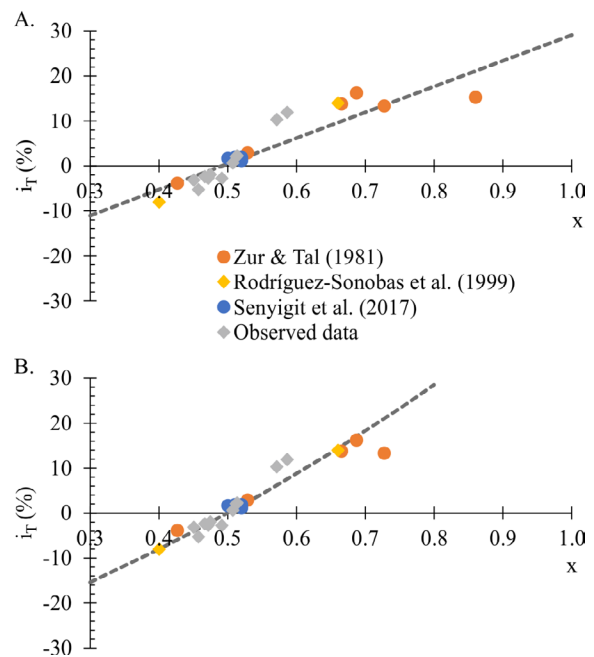


Figure 4. Temperature discharge index (i_T) as a function of the emitter flow exponent (x) in the temperature range of 20 to 40 °C: (A) comparison between the adjustment proposed by Decroix & Malaval (1985) and the data observed in this study and other authors; (B) comparison between the theoretical adjustment proposed by Rodríguez-Sinobas et al (1999), the data observed in this study and the data observed by other authors

increasing the temperature for each emitter. In this study, the increase in discharge as a function of water temperature does not have a unique response; however, it depends on the value of the emitter flow exponent.

CONCLUSIONS

1. The emitter discharge sensitivity to water temperature is related to the flow exponent value of the emitter.
2. The emitter discharge sensitivity to water temperature varied according to the emitter model, but there were no significant differences due to the wall thickness of the drip tape.
3. The temperature discharge index (i_T) had a linear function with negative slope for flat emitters; the power-law function for the welded turbulent flow emitters was ascending for models with $x > 0.5$ and descending for models with $x < 0.5$; and an exponential function for the embossed emitter.

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