Flow Rate and Discharge Coefficient Behavior of Spray Nozzles in a PWM System

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Abstract.

Pulse width modulation (PWM) technology has been widely used in variable-rate pesticide applications, allowing flow control by varying the duty cycle while maintaining constant pressure. However, the intermittent operation of the flow may alter the hydraulic behavior of spray nozzles, influencing both the effective flow rate and the discharge coefficient (Cd). In this context, the objective of this study was to evaluate the behavior of flow rate and discharge coefficient of different spray nozzles operating under a PWM system at a frequency of 25 Hz, analyzing the influence of duty cycle on hydraulic performance. Six nozzles from the manufacturer TeeJet® were evaluated: XR 110015, XR 11002, XR 11003, XR 11004, AI 110015, and AI 11003. The XR nozzles were tested at pressures ranging from 100 to 400 kPa, while the AI nozzles operated within a range of 200 to 500 kPa, according to the manufacturer's recommendations. The system was configured with a fixed frequency of 25 Hz, with duty cycles ranging from 10 to 100%, at 10% intervals. Flow rate was determined by collecting the sprayed volume in a graduated cylinder over one minute and expressed in L min $^{-1}$. To determine the discharge coefficient, a linear regression was fitted between volumetric flow rate and the square root of the applied pressure, obtaining the slope of the regression line (k). The Cd was then calculated based on the modified Bernoulli equation, using the density of the sprayed fluid, the nozzle orifice outlet area, and the experimentally obtained slope coefficient. The data were subjected to Tukey's test at a 5% probability level. The results showed a progressive increase in flow rate with an increasing duty cycle for all evaluated nozzles. At 10% duty cycle, no operation was observed. The XR 11004 nozzle exhibited the highest flow rates at all evaluated levels, reaching 1.57 L min $^{-1}$ at 100% duty cycle, differing statistically from the others. The XR 110015 and AI 110015 nozzles presented the lowest flow values, consistent with their smaller orifice areas. The discharge coefficient also increased with duty cycles. The XR nozzles showed higher Cd values, reaching levels close to 1.0 at 100% duty cycle, with no significant difference among these models. In contrast, the AI nozzles showed significantly lower coefficients, with maximum values below 0.40, attributed to hydraulic losses resulting from the air-induction system. At duty cycles below 20%, Cd values were reduced and even null, highlighting operational limitations of the system at 25 Hz within this range. It is concluded that, at a frequency of 25 Hz, the PWM system presents linear and consistent behavior at medium and high duty cycles. Proper nozzle selection is essential to ensure hydraulic efficiency, flow stability, and precision in variable-rate applications.

Keywords.

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Duty cycle; 25 Hz frequency; Air induction; Hydraulic efficiency; Variable-rate application.

INTRODUCTION

Pulse Width Modulation (PWM) technology enables electronic flow rate control by varying the valve opening and closing times, allowing more precise adjustments of the application rate without requiring constant changes in operating pressure (Jeon and Zhu, 2022; Han et al., 2024). When PWM systems are used, factors such as modulation frequency and duty cycle can alter the hydraulic behavior of spray nozzles and, consequently, affect the discharge coefficient. Understanding these interactions is essential for the proper design and calibration of spraying systems, contributing to greater accuracy in pesticide applications (Guler et al., 2007).

Despite the widespread adoption of PWM technology in agriculture, information regarding the discharge coefficient behavior of different nozzle models operating under varying combinations of pressure, frequency, and duty cycle remains limited. Thus, the purpose of this study was to assess how these operational parameters affected the flow rate and discharge coefficient of spray nozzles that were controlled by pulse width modulation.

MATERIALS AND METHODS

Two experiments were conducted. The first aimed to determine the flow rate of the selected nozzle models by evaluating the effects of modulation frequency and duty cycle under PWM control. The second experiment consisted of determining the discharge coefficient of the same nozzles in order to identify possible variations resulting from the operational parameters.

Six spray nozzle models were selected for the study. The selection was based on the nozzle outlet orifice areas reported by Guler et al. (2007) and included the following TeeJet® nozzles: XR 110015, XR 11002, XR 11003, XR 11004, AI 110015, and AI 11003. The XR nozzles are recommended for contact herbicides, fungicides, and insecticides (except at pressures below 200 kPa, where they are recommended for systemic products), whereas the AI nozzles are intended for systemic applications and drift reduction. Operating pressures were selected according to the manufacturer's catalog, being 100, 200, 300, and 400 kPa for the XR nozzles and 200, 300, 400, and 500 kPa for the AI nozzles.

PWM Flow Control System

A Pulse Width Modulation (PWM) controller was developed using a TeeJet® solenoid valve, a 12 V power supply, a diode, a resistor, an I²C module, an LED display, and three control buttons. The buttons were used to activate the system and to configure the operating frequency and duty cycle. The controller was programmed in C++ using the Arduino IDE® platform. The operating frequency evaluated in this study was 25 Hz, and the duty cycles tested were 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%.

Flow Rate Determination

Flow rate measurements were performed at an operating pressure of 300 kPa, corresponding to the nominal pressure specified for the nozzles according to ISO 10625. Flow rate was determined by collecting the spray solution discharged from each nozzle in a graduated polypropylene cylinder with a capacity of 1000 mL and a resolution of 5 mL, following ISO 5682-1 (2017). The collection period was one minute, measured using a standard digital stopwatch available on an Android device. Flow rate values were expressed in liters per minute (L min^{-1}).

Discharge Coefficient Determination

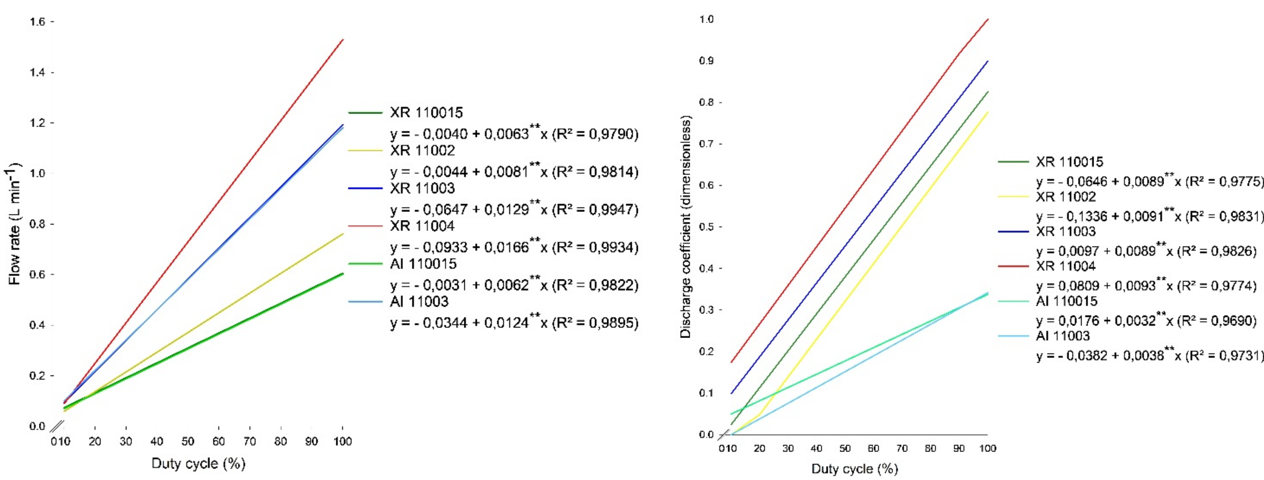
The discharge coefficient (Cd) of a spray nozzle is defined as the ratio between the actual flow rate and the theoretical flow rate through an orifice under the same pressure differential (Srivastava et al., 2006). This dimensionless coefficient reflects energy losses associated with real fluid flow, including internal friction, turbulence, jet contraction, nozzle material characteristics, and orifice geometry. Determining Cd is essential for characterizing the hydraulic efficiency of spray nozzles under different operating conditions. In the presence of the PWM control system, the discharge coefficient can also be used as an indirect indicator of the effects caused by the opening and closing cycles of the solenoid valve.

Statistical Analysis

The experimental data were subjected to regression analysis, and individual models were fitted to describe the relationship between duty cycle and the evaluated variables. Model significance was assessed using the t-test at a significance level of 1%, considering the coefficient of determination (R^2) and the behavior of the studied phenomenon. For the flow rate analysis, data obtained at 300 kPa were used. All statistical analyses were performed using the RStudio software.

RESULTS AND DISCUSSION

The variation in duty cycle significantly affected both the flow rate (Figure 1A) and the discharge coefficient (Figure 1B) of all evaluated nozzles. The fitted models describing flow rate behavior indicated that more than 97.60% of the variation in flow rate was explained by changes in duty cycle for all nozzle types. For the discharge coefficient, coefficients of determination exceeded 96.90%. For both variables, a strong linear relationship with duty cycle was observed, indicating that this parameter plays a fundamental role in the operational adjustment of spray nozzles under PWM control.



(A) (B)

Fig. 1. Fitted models describing the behavior of flow rate (A) and discharge coefficient (B) as a function of duty cycle for the evaluated spray nozzles operating at 25 Hz. Where y = flow rate (L min^{-1}) or discharge coefficient (dimensionless); *x* = duty cycle (%); R^2 = coefficient of determination; ** significant at the 1% probability level by the t-test.

For the discharge coefficient (Cd), the XR nozzle series exhibited steeper regression slopes than the AI nozzles, indicating greater hydraulic efficiency and lower energy losses during flow. The XR 11004 nozzle stood out by maintaining high Cd values throughout the entire duty cycle range, reaching values close to 1.0 at 100% duty cycle. In contrast, the XR 110015, XR 11002, and AI 11003 nozzles showed negative intercepts, suggesting a greater influence of pulsation at low duty cycles and, consequently, increased hydraulic losses under these operating conditions.

Similar results were reported by Campos et al. (2024), who observed a linear increase in flow rate as a function of duty cycle in PWM systems, and by Fabula et al. (2021), who also found a linear flow-rate response, although pressure reductions were observed during operation. Likewise, Salcedo et al. (2022) reported that nozzles with higher nominal flow rates exhibited greater increases in flow rate and distinct behavior among nozzle models. The present findings are also consistent with those reported by Post et al. (2017), who obtained discharge coefficient values that were ranging from 0.87 to 0.90 for flat-fan nozzles operating under conventional spraying conditions, values like those observed for the XR nozzles at higher duty cycles. Overall, the results indicate that under PWM operation at 25 Hz, XR nozzles provide greater hydraulic efficiency and lower sensitivity to pulsation effects, making them more suitable for applications requiring high precision in application-rate control.

CONCLUSION

Operation of the PWM system at a frequency of 25 Hz resulted in a linear relationship between duty cycle and flow rate for all evaluated nozzles, demonstrating the system's ability to modulate the application rate in a predictable and consistent manner. The XR nozzle series exhibited higher discharge coefficients and lower sensitivity to pulsation effects compared with the air-induction (AI) nozzles, indicating greater hydraulic efficiency under high-frequency operation. Therefore, the results demonstrate that PWM technology operating at 25 Hz is a viable alternative for variable-rate applications, provided that the hydraulic characteristics of the selected nozzles are considered to ensure greater precision and uniformity of application.

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