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Research Paper

An iris mechanism for variable rate sprinkler irrigation

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Variable rate irrigation intends to supply water at the right time and place in order to improve water-use efficiency, save energy and decrease nutrient leaching. The concept of an adjustable orifice sprinkler using an iris mechanism actuated by a stepper motor for use in variable rate irrigation was proposed and developed. A prototype was manufactured using additive manufacturing techniques. Its operational characteristics were evaluated. To predict the flow rate, a deterministic model that represented the operation of the sprinkler was proposed and validated. The observed discharge coefficients varied according to the operating conditions, these being: 0.530 when the orifice was fully opened; and an average of 0.636 when the iris mechanism reduced the orifice section. For the condition of a partially opened orifice, the phenomenon of jet inversion occurred causing the jet to become asymmetrical. The proposed concept allows flowrates closer to the required values to be obtained and consequently provides greater flexibility and accuracy to applying the target irrigation depth.

1. Introduction

As water supplies become limited due to competition from encroaching urbanisation, efforts to maximise irrigation efficiency will have to increase to irrigate the same land area with fewer resources (Dukes & Perry, 2006). Globally, about 70% of freshwater is used for agriculture, with irrigation the major user of water (Hedley & Yule, 2009). Thus, irrigation management has evolved into a high priority issue (Haghverdi, Leib, Washington-Allen, Buschermohle, & Ayers, 2016).

Precision agriculture has been seeking approaches to improve agricultural processes by considering the variability of spatial–temporal production factors (Armindo, Botrel, & Garzella, 2010). Variable rate irrigation (VRI) intends to supply water to crops in a precise quantity, at the right time and place

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Nomenclature

Symbols

B/B'	Blade edge in the initial and movement condition, m
C_c	Contraction coefficient, dimensionless
C_d	Discharge coefficient, dimensionless
C_v	Velocity coefficient, dimensionless
D	Orifice diameter, m
g	Gravitational acceleration, m s^{-2}
H	Operation pressure head, m
q	Flow rate, m^3 s^{-1}
r/r'	Orifice radius in the initial and movement conditions, m
$r_1, r_2/r'_1, r'_2$	Segments of orifice radius in the initial and movement conditions, m
R	Correlation coefficient, dimensionless
R^2	Determination coefficient, dimensionless
S/S'	Section flow in the initial and movement conditions, m^2
X_1,X_2,X_3 /X'_1,X'_2,X'_3	Sides of the triangle in the initial and movement conditions, m
$Z_1,Z_2/Z'_1,Z'_2$	Segments of X_2 in the initial and movement conditions, m
$\alpha_1, \alpha_2, \alpha_3/\alpha'_1, \alpha'_2, \alpha'_3$	Internal angles of the triangle in the initial and movement conditions, degrees

Abbreviations

CFD	Computational fluid dynamics
CTI	Renato Archer Information Technology Centre
EEPROM	Electrically erasable programmable ready-only memory
ESALQ	College of Agriculture “Luiz de Queiroz”
FDM	Fused deposition modelling
LEMI	Irrigation testing laboratory
PWM	Pulse-width modulation
RMSE	Root mean square error
STL	Standard triangle language
USB	Universal serial bus
USP	University of São Paulo
VRI	Variable rate irrigation

in order to improve water-use efficiency, thereby increasing productivity, saving energy and decreasing nutrient leaching (Pan, Adamchuk, Martin, Schroeder, & Ferguson, 2013).

Centre pivots and linear-move sprinkler machines are commonly used as pressurised irrigation systems all over the world and present high potential irrigation efficiency (Faci, Salvador, Playán, & Sourell, 2001). These sprinkler irrigation systems are suitable for variable rate application development due to their wide coverage area, high level of automation and are increasingly used by farmers (Evans, Larue, Stone, & King, 2013; Kranz, Evans, Lamm, O'Shaughnessy, & Peters, 2012). Moreover, the potential water conservation and the efficiency of centre-pivot and linear-move irrigation systems may be enhanced by applying variable amounts of water along the lateral line to correspond with variable soil or crop conditions (Dukes & Perry, 2006). Hedley and Yule (2009) compared VRI to conventional uniform irrigation methods and found that 9–19% of irrigation water was saved.

Research has justified the use of precision irrigation through modelling to establish scheduling of irrigation by management zones (Ceresoli, Sobenko, Kreitlov, & Armindo, 2016; Haghverdi, Leib, Washington-Allen, Ayers, & Buschermohle, 2015; Miller et al., 2018). Commercially available technologies for VRI enable sector and zone control. Sector control technologies are simpler and allow a limited number of rectangular sectors for linear-move systems or several pie-slice shaped sectors for centre pivots. In this case, the variable rate application occurs due to changes in the travelling speed, but the discharge of the emitters remains unchanged. On the other hand, zone control technologies are more complex and enable to adjust the irrigation depth in each individual sector by changing the output of emitters. The mechanism for controlling the flow rate of each sprinkler is based on the duty cycle of a solenoid valve installed at the inlet of each emitter, i.e. pulse-width modulation (PWM). However, due to the numerous cycles of opening/closing solenoid valves, pressure regulators may have their lifespan reduced. Furthermore, there are concerns about how the on/off cycles influence water distribution patterns and application uniformity (Dukes & Perry, 2006; King & Kincaid, 2004). For anhydrous ammonia application, Bora et al. (2005) evaluated the reliability of a variable-rate system using PWM solenoids cycling at 15 Hz for 60 h. The authors could not estimate the lifespan of the valves, but 84% of them operated effectively in these conditions. Han, Hendrickson, Ni, and Zhang (2001) evaluated a variable-rate control system consisted of PWM solenoids in several individual nozzles for nitrogen application. By the volumetric tests carried out, the results showed that the primary causes of the inaccuracy are the valve-to-valve differences in flow rate response to PWM signals, presenting calibration errors ranging from −15 to 20%.

On the development of zone control technologies, King and Kincaid (2004) and Armindo et al. (2010) proposed prototypes of sprinklers for centre pivots or linear-move systems. The discharge of their prototypes was adjusted by displacing an internal concentric rod that changes the nozzle flow section. King and Kincaid (2004) reported that the spray became finer and the wetted radius decreased about 15% due to the interference of the rod in the flow through the nozzle. Both researches indicated that variable rate sprinklers based on a concentric pin that moves into a sprinkler nozzle bore was a feasible concept.

Another potential approach for obtaining variable discharge emitters consists of using an iris or diaphragm mechanism to adjust the flow cross-section of an orifice. Iris-type mechanisms are usually formed by a combination of overlapped metal blades that form an adjustable orifice enabling control of aperture sizes and have been used in several applications such as imaging systems (Ren, Park, Ren, & Yoo, 2012), optics (Syms, Zou, Stagg, & Veladi, 2004), radiotherapy (Graves et al., 2007), energy beam collimators (Hill, 1984), lens technology (Chang, Peng, & Chan, 2000), robotic radiosurgery (Echner et al., 2009), and solar reactors (Rajan et al., 2016).