ISSN 0719-3882 print
ISSN 0719-3890 online

Review

CONTROL AND AUTOMATION OF FERTIGATION IN AGRICULTURAL CROPS

Revisión

CONTROL Y AUTOMATIZACIÓN DE FERTIRRIGACIÓN EN LOS CULTIVOS AGRÍCOLAS

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ABSTRACT

Irrigated agriculture is one of the major water-consuming sectors. However, fresh water is a limited resource, which is now under an unprecedented pressure due to global population growth and climate changes. To assure the development of the plants and maximize crop yields, a suitable water and nutrient supply is required. Concentrated fertilizer dissolved in irrigation water before its application to the plants (fertigation) should result in benefits when compared to conventional fertilization. In this review article, the main concepts associated to the control and automation techniques applied to fertigation are presented. The adoption of these techniques can result in water and fertilizer savings, contributing to less environmental contamination.

Key words: nutrient delivery systems, electrical conductivity, pH, pumps, Venturi.

RESUMEN

La agricultura irrigada es uno de los sectores que más consume agua. Sin embargo, el agua fresca es un recurso limitado que de hecho está sometido a una presión sin precedentes debido al crecimiento de la población global y cambios climáticos. Para asegurar el desarrollo de las plantas y aumentar al máximo los rendimientos de los cultivos agrícolas, es necesario un suministro de agua y nutrientes adecuado. La disolución de fertilizantes concentrados en el agua de irrigación, antes de su aplicación a las plantas (fertirrigación), puede producir beneficios en comparación con la fertilización convencional. En éste artículo de revisión se presentan los conceptos principales asociados al control y automatización de la fertirrigación. La adopción de estas técnicas puede propiciar economía de recursos hídricos y fertilizantes, contribuyendo a una menor contaminación ambiental.

Palabras clave: sistemas de aplicación de nutrientes, conductividad eléctrica, pH, bombas, Venturi.

Received: 14 August 2013. Accepted: 09 September 2013.

INTRODUCTION

Fertilizer applications in agricultural crops can be done by using granular fertilizers, which are directly incorporated into the soil/substrate before sowing or transplanting seedlings, or by using top-dressing through plant growth and development. Controlled-release fertilizers should also be mixed with soil/substrate prior to or during crop cultivation. On the other hand, liquid fertilizers should be applied directly to the plant leaves (foliar fertilization). According to Boodley and Newman (2008), good results have also been obtained using a technique that consists of dissolving granular fertilizers or concentrated fertilizer solutions in irrigation water before their application to the plants (fertigation). Compared to the conventional cultivation, fertigation can promote savings of around 50% of water during the crop cycles (Stanghellini, 1993; Leonardo et al., 2008).

One of the main advantages of fertigation is the rational fertilizer application, which allows optimizing water and nutrient supply in agreement with the crop nutritional requirements (López, 2005). Additionally, this technique allows the monitoring of the concentrated nutrients dissolved in irrigation water by using electrical conductivity, ion selective electrodes or ion selective field effect transistor probes. Depending on crop nutrient requirements, two or more injectors should be necessary in a fertigation system, since the mixing of specific fertilizers in very high concentrations can cause the precipitation of some nutrients in the stock solution reservoir, making them unavailable to the plants (Hanan et al., 2012).

Testezlaf and Matsura (1999) indicated that the activities associated with fertigation should be totally or partially automated by using control systems capable of considerable savings of water resources, electrical energy, fertilizers and labor. According to these authors, a suitable crop management associated to fertigation automation can result in less environmental contamination and increased crop quality and yield.

Improvement of fertilizer application technologies such as fertigation automation is essential to maintain equilibrium between the production of plants, flowers and fruits and their growing demand. In addition, both sustainability of fertigated crop systems and preservation of the environment depend on conducting suitable water and fertilizer management practices (Papadopoulos, 1999).

The objective of this review is to contribute to the diffusion of the main control and automation techniques applied to fertigation, increasing the knowledge of technicians, researchers, engineers and other professionals working in agricultural sciences about sensors and injection systems of concentrated fertilizer solutions in the irrigation water.

CONTROL SYSTEMS

A system can be defined as an interconnected component set, capable of carrying out an operation. In particular, a control system can be defined as a system that can monitor or regulate an operation or process. Monteiro (2002) indicated that a control system is composed of inputs, perturbations or disturbances and outputs. Inputs represent the commands sent to the system, while perturbations or disturbances change the controlled variables. Finally, outputs are actions that may be executed in order to maintain the controlled variables within the preset limits. Thus, the function of a control system is to regulate the values of the controlled variables when perturbations change them. This is done by using actuators, such as pumps, injectors, valves, among others.

Two general types of controllers can be used in agricultural cultivation: open-loop and closed-loop control systems (Zazueta et al., 2002). In both of them, a control strategy is used to manage the decision making about what may be executed by the actuators. Bolton (2002) indicated that there are different types of control strategies, which should be chosen according to the application. In open-loop control systems, the on/off strategy is the most widely used because it is simple and inexpensive. This control strategy allows only two actuator status: turned on with maximum power or completely turned off. However, other strategies are also employed in closed-loop control systems, such as proportional, integral, and derivative controls, as well as their combinations. Strategies based on computational methods, such as neural networks, mathematical models, genetic algorithms, and fuzzy logic, have also been developed (Samsuri et al., 2010; Hansen et al., 2011; Shekofteh et al., 2012). These strategies require more sophisticated controllers, but reduce the steady-state errors and allow intermediary actuator status. They are appropriate for a kind of system with nonlinearity uncertainties and disturbances, acting in a preventive way and improving control efficiency (Thanh and Ahn, 2006).

Open-loop fertigation control systems

A control system is called open-loop when the output variable does not influence the control action, that is, the output is neither measured nor feedbacked to be compared to the input (D'Azzo et al., 2009). In this case, an input signal or command is applied to the controller and the output signal acts on the process, setting the controlled variable to a desired condition (Golnaraghi and Kuo, 2009). When disturbances or perturbations occur, this control type is not capable of carrying out the desired operation with precision due to the lack of error correction mechanisms (Ogata, 2009).

In an open-loop control system for fertigation, the operator may make the decision concerning the amount of concentrated fertilizer solution that will be diluted in the irrigation water, along with the duration and frequency in which fertigation will be conducted. These data are set in the controller according to a desired schedule.

The simplest open-loop control systems applied to crop fertigation are composed of a timer that controls the fertilizer solution injector according to a time interval preset by the user (Fig. 1).

Zazueta et al. (2002) described timers as simple controllers composed of time-measuring electromechanical or electronic devices capable of activating one or more actuators through electromagnetic relays. Several designs are commercially available providing different features, flexibility regarding controller programming and a wide range of prices.

The main disadvantage of open-loop control systems is the controller inability to automatically respond to environmental conditions (Testezlaf and Matsura, 1999). In addition, depending on the application, these controllers may require frequent adjustments in order to avoid the decrease in water and nutrient use efficiencies.

Closed-loop fertigation control systems

A control system is called closed-loop when its output signal influences the control action, that is, when the system is feedbacked. In this case, an error signal, which is the difference between the input and the feedback signals, is constantly monitored and used by the controller to adjust the output signal to a desired value (Dorf and Bishop, 2010).

The main advantage of the closed-loop systems is that the feedback reduces the sensitivity of the system response to external perturbations and to internal variations in the system parameters. Thus, closed-loop control systems are more precise (Ogata, 2009). However, these systems are more complex and much more expensive (Nise, 2010).

More sophisticated control strategies should be developed and implemented in closed-loop control systems for fertigation when compared to open-loop ones. Once the strategy is defined, the control system should make decisions about the most appropriate fertigation duration and frequency. This should be done automatically and in real-time, based on data from one or more probes connected to the controller (Boman et al., 2002).

One possibility is to apply closed-loop systems to crop fertigation by controlling fertilizer solution concentration based on electrical conductivity measures (Fig. 2). In these cases, the decision making process is done by comparing actual conditions, which are represented by the real-time measurements, to the desired ones, which are preset in the control strategy. After that, preventive or corrective actions are executed by actuator devices in order to minimize the differences between desired and measured values.

SENSORS

Sensors are important components of closed-loop control systems. These provide information that feedback the control strategy associated with the decision making process. According to Taylor (2010), sensors are devices that convert physical quantity into analogical or digital signals. In this

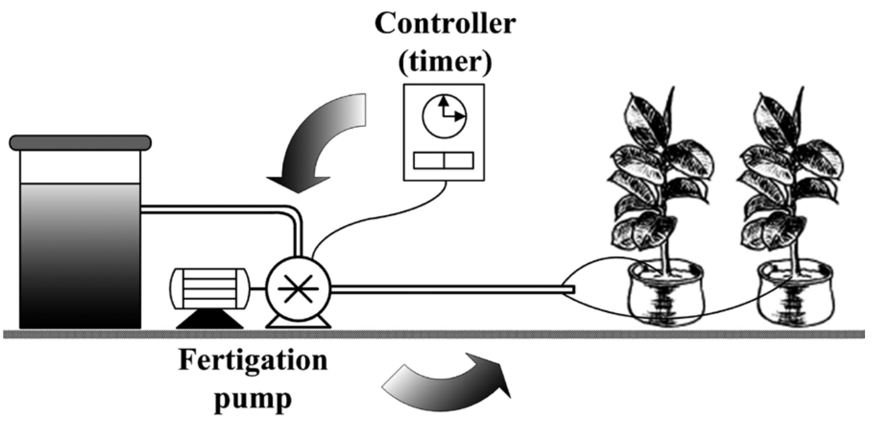

Fig. 1. Time-controlled open-loop fertigation system.

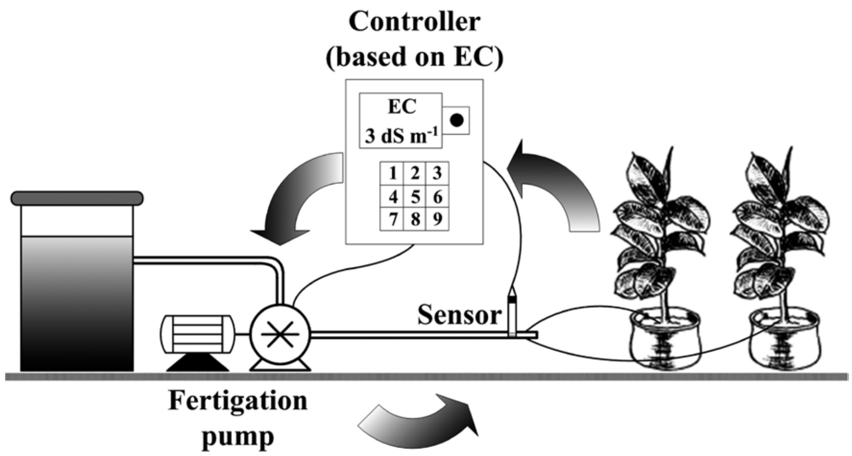

Fig. 2. Closed-loop fertigation system based on electrical conductivity probe.

review, electrical conductivity (EC) and hydrogenionic potential (pH) sensors will be discussed according to their relevance for fertigation control and automation.

Electrical conductivity sensors

Electrical conductivity is defined as the ability of an aqueous solution to conduct electrical current (Colombié et al., 2007) and in the International System (SI) of units it is measured in deciSiemens per meter (dS m^{-1}). This unit is equal to miliSiemens per centimeter (mS cm^{-1}), which is frequently used for expressing the fertilizer solution concentrations applied to agricultural crops.

Conductivity may be measured by applying an alternating electrical current to two electrodes of a conductivity cell immersed in an aqueous solution and measuring the resulting voltage. During this process, cations migrate to the negative electrode, anions to the positive electrode and the aqueous solution acts as an electrical conductor transporting charge through these ions (Radiometer Analytical, 2004).

Basically, an electrical conductivity cell consists of two concentric metallic cylinders (electrodes) whose spacing and areas are precisely established. The cylinders are mounted into a cavity built with an insulating material, usually glass or plastic. This cavity limits the solution volume which will be measured. Consequently, electrical conductivity measurements become independent of the sample total volume and the proximity of surfaces such as bottle or pipe walls (Steidle Neto et al., 2005).

Among the main variables that can influence electrical conductivity measurements, conductivity cell geometry and aqueous solution temperature are emphasized (Radiometer Analytical, 2004).

With respect to electrical conductivity cell geometry, both length of the column of liquid between the electrodes (L) and area of the electrodes (A) are the most important dimensions (Cole-Parmer, 2006). The ratio L A^{-1} determines the cell constant (K), which affects the electrical conductivity values. This constant changes with time due to contamination or physical-chemical modification, which is present mainly in cells with platinized electrodes. Walker (2007) indicated that the electrical conductivity cells used in agricultural applications usually have a constant value (K) of 1 cm^{-1}.

Electrical conductivity is directly proportional to temperature. The solution resistance to the electrical current flow decreases as the temperature rises, resulting in an increase in the conductivity and vice versa. This effect is due to the solution ion mobility that increases with temperature. Therefore, solution temperature measurements may be accomplished simultaneously with electrical conductivity ones for compensation purposes. These measurements are usually obtained by using temperature probes, as thermistors, which are included inside the electrical conductivity cell. Solution electrical conductivity may even be related to the reference temperature of 25°C for standardization purposes (WTW, 2008).

As electrical conductivity measurements provide the total amount of ions dissolved in the solution, it has been the basis of most used techniques to control fertilizer solution concentrations in agricultural crops (Steidle Neto, 2007). This method is practical and presents a relatively low cost. However, a most sophisticated control technique for this purpose is based on the individualized concentration measurement of each nutrient present in the fertilizer solution. This is done by using ion selective electrode (ISE) and/or ion selective field effect transistor (ISFET) sensors which have permeable membranes to specific ions. According to Van Os et al. (2002), the in situ, real-time and individual measurements of all nutrient concentrations in the fertilizer solution is currently not feasible in commercial scale. A few practical limitations related to ISE and ISFET sensors have been solved, in particular, stability and robustness of measuring systems (Gieling et al., 2005). However, some inherent properties of the sensors, such as lifetime, drift, temperature and light sensitivity still require to be improved (Jimenez-Jorquera *et al*., 2010).

Hydrogenionic potential sensors

The hydrogenionic potential is directly related to the concentrations of hydrogen (H^+) and hydroxyl (OH^-) ions present in aqueous solutions. The pH scale varies from 0 to 14, with values of seven representing neutral conditions, that is, the number of H^+ and OH^- ions are equal in the solution. Values of pH greater than seven are considered alkaline (less H^+ ions than OH^- ones). On the contrary, the pH in an acid solution is smaller than seven and there are more H^+ ions than OH^- ones (Malavolta, 2006).

Measurements of pH can be accomplished by calorimetry or potentiometry. The calorimetric method is based on indicators that turn a unique color at a specific pH value. The indicators themselves are organic compounds that, in aqueous solutions, undergo color changes indicative of the acidity or alkalinity of the solution (Flott, 2002). The potentiometric method is characterized by the comparison of two solution hydrogenionic potentials. The reference solution has a well-known pH and is contained inside the electrode. The other one is the solution whose pH will be determined. The signal generated by the pH electrode is the electrical voltage measured between the solutions (Zolnier, 2004).

The temperature of the fertilizer solution in which the pH electrode is immersed influences measurements (Cole-Parmer, 2003). Thus, similarly to electrical conductivity probes, the solution temperature may be simultaneously measured with the pH for compensation purposes.

The fertilizer solution pH can be controlled by adding acids (sulfuric, phosphoric, nitric or chloridric) or strong bases (sodium, potassium or ammonium hydroxides) aiming to reduce or increase the pH, respectively. In general, automation of pH correction and monitoring are composed of electrodes, which are partially immersed in the fertilizer solution applied to the plants. These electrodes are connected to a controller that activates pumps for acid or alkaline solution injection (Rodrigues, 2012).

Aiming to improve the pH automatic control, the fertilizer solution can be adjusted from water electrochemical decomposition in H^+ and OH^- ions by using specific cells (Spinu et al., 1998). These electrochemical cells comprise an ion exchange membrane that is divided in two compartments (cathode and anode), where the ions are generated according to the solution acidity or alkalinity. An experimental evaluation of electrochemical pH control in a NFT hydroponic unit for butterhead lettuce was performed by these authors. The results obtained in this experiment showed the pH control efficacy with a rather modest consumption of electrical energy.

INJECTION SYSTEMS OF CONCENTRATED FERTILIZER SOLUTIONS

The purpose of an injection system is to accurately dose and incorporate one or more concentrated fertilizer solutions in the irrigation water before their application to the plants. Trani and Carrijo (2004) classified injection systems as quantitative or proportional. Quantitative injection systems are characterized by the decrease in fertilizer solution concentration along the time, as fertigation events occur. The proportional injection systems are those in which the concentrated fertilizer solution is mixed in the irrigation water according to constant and proportional rates as fertigation events occur. Thus, solution concentration is not changed over time in proportional systems.

Quantitative injection systems are not recommended for agricultural crop fertigation due to the disadvantages associated with fertilizer solution concentration control. Therefore, a more detailed discussion will be provided in this review, considering the main proportional injection systems, which can be divided into positive pressure or negative pressure systems.

Positive pressure injection systems

These systems remove the concentrated fertilizer solution from an unpressurized reservoir and incorporate it into the irrigation water piping, always providing a positive pressure (Pizarro, 1999). The injectors can be activated by electrical or hydraulic energy. When the second option is adopted, the water into the irrigation piping is used as driving force (Zanini et al., 2002).

Centrifugal pumps can be used to inject concentrated fertilizer solutions in the irrigation water (Fig. 3), although they are not specific for fertigation. To operate as a concentrated solution injector, it is necessary that the centrifugal pump produces a pressure higher than that existing inside the water piping. However, the concentrated solution injection rate depends on the pressure in the irrigation piping. Thus, high pressure in the irrigation piping results in small injection rate and vice versa (Haman et al., 2003b). Because of this, centrifugal pumps require calibration, which is done by maintaining the pump in operation and adjusting the pressure and flow in the irrigation piping until the fertilizer solution electrical conductivity reaches a desired value after the injection point.

As the concentrated fertilizer solution volume diluted in each fertigation is reduced, small centrifugal pumps (7.5 to 32 W) should be used as concentrated solution injectors (Steidle Neto et al., 2009).

Diaphragm pumps are the most frequent concentrated fertilizer solution injectors used in agricultural applications. Zanini et al. (2002) indicated that a diaphragm pump is composed of a brass chamber that contains two valves (suction and discharge) and two diaphragms interconnected to a shaft. Initially, the ascendant movement of the shaft reduces the pressure inside the chamber, providing suction in the lower section of the diaphragm. Then, the concentrated solution is aspirated to the interior of the chamber through the suction valve. When suction finishes, the descendant movement of the shaft creates a high pressure inside the chamber. So, the suction valve is closed and the discharge valve is opened, forcing the concentrated solution to exit and, consequently, mixing with irrigation water (Fig. 4).

A major advantage of diaphragm pumps is that the concentrated solution does not come into contact with most of the working parts of the pump. The only moving parts that are in contact with the pumped liquid are the diaphragm and the suction/discharge valves. Hence, diaphragm pumps are suitable for pumping corrosive solutions, which is often the case with chemical in-

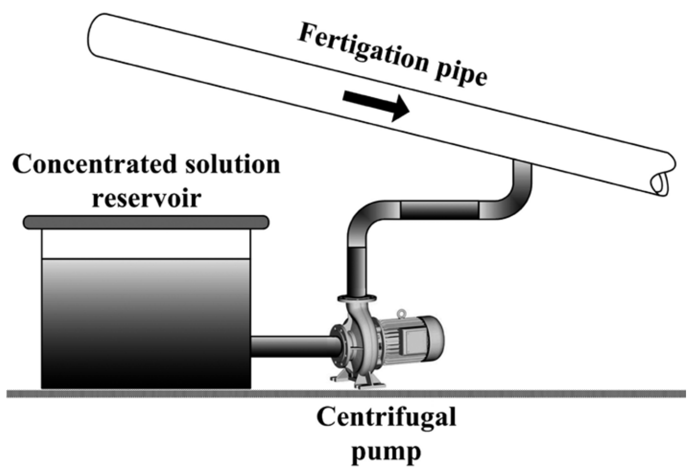

Fig. 3. Centrifugal pump operating as concentrated fertilizer solution injector.

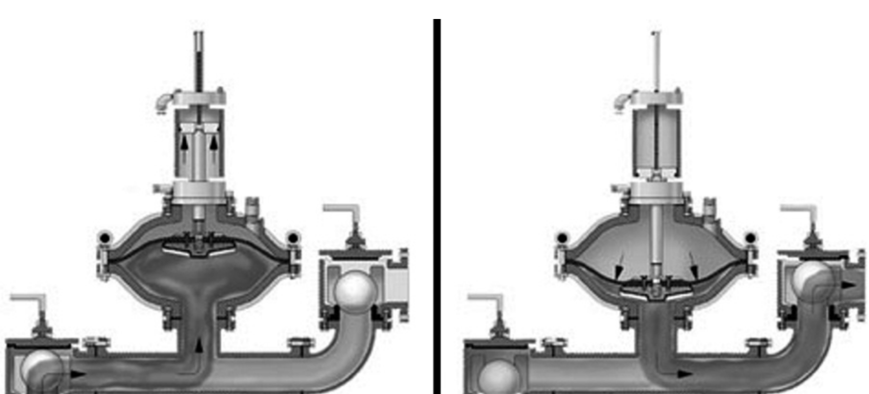

Fig. 4. Operating principle of a diaphragm pump (suction - left and discharge - right).

jection into an irrigation piping (Haman et al., 2003a).

Due to changes in the sources that activate the diaphragm pump, application rates of concentrated fertilizer solution in the irrigation water can vary (Burt et al., 1995). To assure that the concentrated solution rate be really proportional in pumps activated by electrical energy, a water flow sensor should be used. This sensor may be installed in the irrigation piping before the concentrated solution injection point, aiming to detect changes in the flow rate and automatically adjust the speed of the injector or injection time (Haman et al., 2003b).

Piston pumps are very accurate and are composed of single or double action piston, which is attached to a mechanical linkage, and transforms the rotary motion of a drive wheel into the reciprocating motion of the piston. According to Boman et al. (2004), in each complete piston cycle, a specific amount of concentrated fertilizer solution is aspirated to the interior of the pump through the suction valve, filling the chamber that involves the piston. While the concentrated solution is aspirated, the discharge valve remains closed due to the pressure difference between the interior and the exterior of the chamber. When the piston performs the opposite movement, the aspirated volume is injected in the irrigation piping through the discharge valve promoting mixing, while the suction valve remains closed (Fig. 5).

Yeager and Henley (2007) indicated that single action piston pumps present the disadvantage of a time interval that always separates each complete cycle. This same problem can also occur with diaphragm pumps. Therefore, uniformity of the concentrated fertilizer solution injection can be affected. This problem should be solved by using double action piston pumps. However, as the oscillation of the injection rate in single action piston pumps is very fast, this variation does not restrict the use of these injectors for agricultural crops.

There are piston pumps in which the concentrated fertilizer solution dosage is constant. Water flow activates the injector, which takes up the required percentage of concentrate directly from a reservoir with concentrated fertilizer solution. The amount of concentrate solution dispensed is directly proportional to the volume of water entering the injector, irrespective of variations in water flow or pressure that may occur in the water piping (Pennisi and Kessler, 2003).

Combined injection pumps are commercially available, in which a piston forces oil or other incompressible fluid against a diaphragm, resulting in the concentrated solution displacement. The main advantage of these pumps is that they combine high precision typical of a piston pump with the resistance to chemicals characteristic of diaphragm pumps (Haman et al., 2003b).

Negative pressure injection systems

In these systems, the concentrated fertilizer solution is suctioned and incorporated into the irrigation water due to the negative pressure generated by the transformation of water pressure energy, which goes through the injector, in kinetic energy (Dourado Neto et al., 2001). Negative pressure injection systems are always activated by using water energy as a driving force. The au-

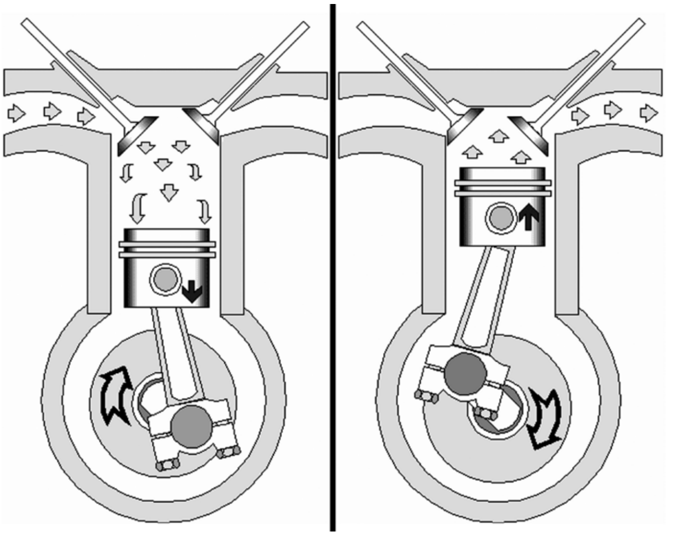

Fig. 5. Operating principle of a piston pump (suction - left and discharge - right).

tomatic control of an injector system activated by hydraulic force requires solenoid valves, which are opened and closed by using a controller.

Venturi injectors (Fig. 6) are the main negative pressure systems used in agricultural applications, comprising a conical convergent section followed by a constriction and by a conical divergent section. This injector operates on the principle that a pressure drop results from the change in velocity of the water as it passes through the constriction. The pressure drop through a Venturi must be sufficient to create a negative pressure (partial vacuum) relative to atmospheric pressure in order for the concentrated solution to flow from a reservoir into the injector (López, 2005). Most Venturi injectors require at least a 20% differential pressure to initiate a vacuum.

A Venturi injector can be connected in parallel to the irrigation piping by using a by-pass line with a smaller diameter. Other possibility is to directly install a Venturi injector in the irrigation piping, what can result in head loss from 30 to 50% of the working pressure (Zanini et al., 2002). However, the head loss observed in the water piping when using the by-pass line should be minimized by a booster pump (Fig. 7), which creates the additional pressure necessary to suitable Venturi injector operation (Trani and Carrijo, 2004).

A Venturi injector does not require external

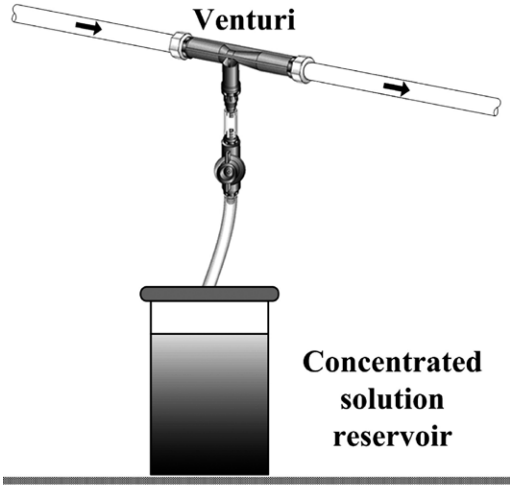

Fig. 6. Typical installation of a Venturi injector for agricultural applications.

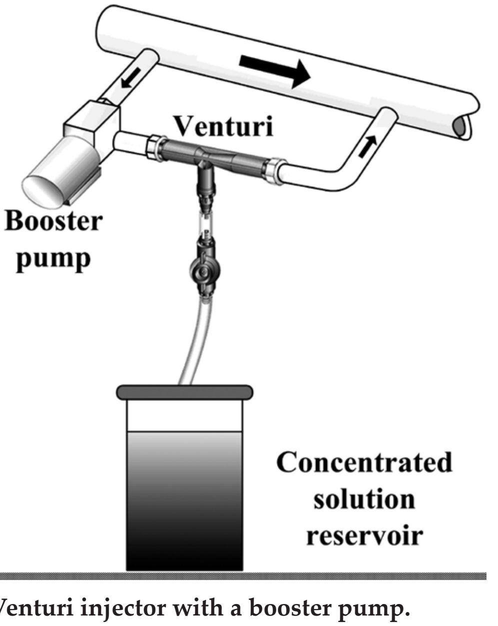

Fig. 7. Typical installation of Venturi injector with a booster pump.

power to operate. There are no moving parts, which increases its life and decrease probability of failure. The injector is usually constructed of plastic, which makes it resistant to most chemicals. It requires minimal operator attention and maintenance, and its cost is low as compared to other injectors of similar function and capability. Venturi injectors come in various sizes and can be operated under different pressure conditions (Boman et al., 2004).

The concentrated solution injection rate varies proportionally to the water pressure that goes through the Venturi injector. Thus, the application rate becomes constant by controlling the pressure. Other important aspect refers to the maintenance of the Venturi injector suction capacity, which depends on maintaining the concentrated solution level always constant into the reservoir. To avoid this problem, some manufacturers provide an additional small reservoir on the side of the supply reservoir, where the float valve maintains solution level relatively constant. The fluid is injected from this additional reservoir (Haman et al., 2003b).

Siphon injectors are small brass mixing valves that operate based on the pressure differential between the irrigation piping and the concentrated solution reservoir. This differential promotes the suction and mixing of the concentrated solution in the irrigation water (Pennisi and Kessler, 2003). The stock solution reservoir may be opened at local atmospheric pressure. These injectors present reduced cost and minimal maintenance requirements. Additionally, they have a device which prevents the concentrated fertilizer solution from backflowing to the reservoir when a drastic pressure drop occurs in the irrigation piping. However, water pressure fluctuations in the irrigation piping result in expressive variations in the amount of suctioned concentrated solution. Therefore, siphon injectors are only recommended for simple applications.

RECENT TRENDS IN FERTIGATION SYSTEMS

Many studies have been carried out in order to evaluate fertigation effects on the plants (Castellanos et al., 2013; Liang et al., 2013; Quintero et al., 2013; Soto et al., 2014). New control strategies and system designs have also been proposed, aiming at providing low cost solutions for precise control of fertilizer mixing and irrigation, always combining basic injection systems and the available control techniques.

Barradas et al. (2012) developed a Decision Support System (DSS) to assist farmers and managers in the process of designing and optimizing irrigation and fertigation systems. These authors have stated that designing fertigation systems involves selection from a large number of combinations of main factors, which become easier to manipulate and rank through the DSS tool. In addition, it is conceived in such a manner that the user may learn through the application process. In a similar research, Incrocci et al. (2012) proposed a DSS tool for fertigation management in soilless culture, which incorporates three main modules: nutrient solution calculation, evapotranspiration simulation, and fertigation management. This DSS can assist growers in the daily operational management of fertigation, as well as in off-line (prior to planting) simulation; for instance, to compare different fertigation strategies, growing system layouts, water qualities and/or crop species in terms of water and nutrients use efficiency.

Salih et al. (2012) developed a system powered totally by solar energy, in which a predefined electrical conductivity value is used as a single input for controlling an automated fertigation system. In this work, fertilizer injectors were centrifugal pumps. In addition, solenoid valves were used to control water flow to the mixing tank and to control nutrient flow to the fertigation system. An ultrasonic sensor was used to monitor nutrient level in the mixing tank. By being fully operated with solar energy, the system can be installed at rural and remote locations to achieve reductions in costs and produce better yield for crops cultivated using fertigation systems. In another study, Domingues et al. (2012) described the development of an automated fertigation system, in which control is accomplished online via webcam and software. In this system, temperature, conductivity and pH measurements were made by sensors and electrodes throughout 24 h during the whole production cycle. It also allows automatical adjustment of any change in the predetermined values, through solenoid valves connected to tanks, which delivery solutions acids, basics or nutrients.

Fertigation is a potential application area for control and automation systems by using sensors and modern technology. Further studies still are required to consolidate and optimize actual fertigation systems, as well as to evaluate their effects on different crops.

CONCLUSIONS

Technologies associated with fertilizer application control and automation in agriculture can assure reliable water and nutrient supply to the crops with consequent yield increase and farmer profitability. By using injection systems correctly, it is also possible to minimize soil or substrate salinization and optimize the use of water, fertilizer and electrical resources. There is an increasing demand for fertigation systems based on new interfaces, standardized platforms and new equipment, aiming at improving this automation process.

The selection of a fertilizer solution injection system in the irrigation water depends on the technical features of the injector, crop economic value, size of the planting area to be fertigated and amount of capital that farmers can invest during cropping, among other factors.

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