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Modeling and design of an injection dosing system for site-specific management using liquid fertilizer

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Abstract

A variable rate of fertilizer according to plant demand and placement (50–100 mm deep) beside roots are essential principles for improving nitrogen use efficiency in growing crops. The objective of this study was to develop an injection dosing system that aligns with site-specific management of nitrogen fertilizer. The implementation considered a process that combines soil perforation and liquid fertilizer injection, which improves fertilizer uptake by the plant. Soil punching can provide nutrients near the plant roots, causing minimal disturbance to roots, crop residues and soil. Liquid fertilizer injection synchronized with soil punching at a variable fertilizer rate was the central idea applied in the design. Based on these requirements, an innovative injection dosing unit was developed. The hydraulic system was modeled inside the Simulink environment, which is linked to Matlab. The program considered the hydraulic elements (primary dimensions) and liquid fertilizer application conditions (forward speed, inter-row spacing of crops and liquid fertilizer rate, source and nutrient concentration). The outputs (simulations of outlet flow, dosage, hydraulic pressure and hydraulic power demand) were essential estimates that assisted in analysis and design. In general, the simulations were analogous to the experimental measurements. Dosage control was applied along a representative range (5–18 ml cycle^{-1}) that allowed application using a variable rate. The liquid fertilizer was injected during soil perforation, from 50 to 100 mm deep. These characteristics can help implement better practices for nutrient stewardship, which are especially relevant for nitrogen fertilization in growing crops, such as sugarcane fields.

Keywords Sugarcane · Management practices · Nitrogen fertilizer · Agricultural machinery · Variable rate

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Introduction

Sugarcane is a semi-perennial crop that is cultivated mostly in tropical and subtropical climates. After the annual mechanical harvest, during the sprouting phase, nitrogen fertilization helps preserve soil fertility and replace nutrients that are exported together with millable stalks. In general, the nitrogen fertilizer is sprinkled beside the ratoon cane rows, broadcasted in side bands on the soil surface or continuously incorporated inside narrow trenches. On the surface, crop residues that remain after sugarcane harvest may favor nitrogen losses to the environment; as a consequence, nitrogen use efficiency is decreased. Despite the benefits of crop residues for soil conservation (nutrient recycling, soil moisture conservation, soil organic matter increment, runoff and soil erosion control), N fertilizer placement on the surface can increase nitrous oxide emission (Fracetto et al. 2017), ammonia volatilization (Costa et al. 2003; Prasertsak et al. 2002) and mineral nitrogen immobilization mediated by soil micro-organisms (Fortes et al. 2012). These unfavorable conditions are especially likely to occur after the application of urea fertilizer, which is the most frequent nitrogen source in the world (Chien et al. 2009). The higher nitrogen concentration and cost of this fertilizer explain its frequent use. On the other hand, N losses from urea placement on the surface can reach up to 40% via ammonia emission (Costa et al. 2003), which is associated with urease activity with a relevant amount of crop residue (10–20 Mg ha^{-1}) (Leal et al. 2013).

It follows that placement of fertilizer at 50–100 mm deep can decrease nitrogen losses to the environment and improve nitrogen use efficiency (Mohanty et al. 1999). However, farmers continue to supply nitrogen fertilizers on the soil surface, especially due to the greater effective field capacity of machines. Additionally, in the crop residue layer (~ 100 mm) (Leal et al. 2013), opener furrows encounter a mechanical barrier to incorporating fertilizer into the soil (Bianchini et al. 2014). In addition, the efficacy of process decreases when associated with restrictions on cutting the crop residue layer. The incorporation of fertilizer together with crop residues and soil clods allows ammonia emission into the atmosphere and damages the root system during furrow opening.

Currently, liquid fertilizers are used less frequently than dry fertilizers in Brazilian agriculture. Liquid fertilizers have advantages, such as lower energy demand during the production phase, mixture homogeneity, dosage control and application quality (Korndörfer et al. 1995). Additionally, a mechanized process for liquid fertilizer injection can overcome the difficulties of incorporating fertilizers in fields with growing crops. The common opening furrows can cause permanent damage in cereal crops, associated with the draught force beside planted rows and roots. Other possible application approaches involve the injection of animal slurry into the soil. The deep placement of liquid biofertilizer (~ 100 mm) can reduce odor and ammonia emission (Chen and Ren 2002; Nyord et al. 2010).

Historically, technological advances have been developed primarily for cereal crops, and the technologies are subsequently transferred to sugarcane production. As one example, despite intense use of machinery for sugarcane production in Brazil, mechanical green cane harvesting significantly increased only in the 2000s (currently, this practice covers over 90% of crops, CONAB 2017). New technologies are relevant for improving conventional practices that are not aligned with environmental protection (e.g., gaseous emissions, nutrient losses, soil erosion and soil compaction). In addition, these technologies can contribute to the adoption of precision agriculture practices (Weber and McCann 2015). Within this context, emerging technologies can also help to improve nitrogen fertilization in growing crops. For nitrogen fertilization, it is essential to consider an appropriate placement for plant uptake and variable rate application according to plant needs. Based on these principles, the objective of this study was to develop an injection dosing system that aligns with site-specific management of nitrogen fertilizer.

Materials and methods

Taking into account the advantages of fertilizer placement into the soil (50–100 mm deep), to implement a site-specific management process for nitrogen fertilization, the proposed system encompasses mechanized soil punching to enable liquid fertilizer injection near the roots of plants while causing minimal disturbance to the soil, roots and crop residues (Silva et al. 2017). The point placement can overcome current difficulties related to common fertilizer incorporation methods (crop residue cutting and soil movement) and reduce damage to the root systems used for nutrient uptake. This system could reduce nutrient losses to the environment, which would be an advantage when using sources associated with ammonia emission, such as liquid urea, liquid ammonia urea and aqua-ammonia. These principles are recommended by the International Plant Nutrition Institute (INPI 2017). The best management practices (BMPs) for nutrient stewardship encourage the application of the right product (source) at the right rate at the right time and the use of the most appropriate placement. This approach is also aligned with conservation tillage, which is associated with non-disruption of crop residues on the soil surface and minimal soil disturbance. In general, minimal tillage protects and conserves soil organic matter and helps erosion control. This approach also has the advantage of a low specific energy demand by the machinery (Dordas 2015).

Working principle

Mechanized soil punching for liquid fertilizer is performed by drilling every 300 mm (on average, between ratoon plants) and injecting liquid at a depth over 50 mm, a condition that is considered sufficient to reduce ammonia emissions to the environment (Fig. 1a, patent BR 10 2013 01821-3) (Magalhães and Silva 2013). Among the characteristics required for liquid fertilizer application aligned with the soil punching process, the hydraulic system must perform injections synchronized with the punching movement; in addition, the applied dosage must be selected according to agronomic recommendations for the fertilizer rate. To achieve these requirements, a reciprocating piston pump was designed, named the "injection dosing unit", taking into account the following principles. When the soil puncher moves above the ground, the pump sucks liquid from the reservoir; then, during the drilling phase, the liquid fertilizer is applied through the injector probe into the soil. For this process, a cam was designed to drive the reciprocating piston pump motion through suction and injection synchronized with the soil punching cycle (Fig. 1b). Synchronicity between soil punching distance (S_{dist}—m cycle^{-1}) and forward speed ($\dot{x}$—m s^{-1}) was sustained by angular velocity control ($\dot{\omega}$—rad s^{-1}) as a function of the punching cycle (T—s), Eq. 1.

$$\dot{\omega} = \frac{2\pi}{T} \therefore T = \frac{S_{dist}}{\dot{x}} \rightarrow \dot{\omega} = \frac{2\pi\dot{x}}{S_{dist}} \tag{1}$$

The dosage volume injected per punching cycle was controlled by a mechanism that allowed fluid to return to the reservoir; thus, the application rate could be varied. For this goal, an injection piston with a groove was designed (Fig. 2), which permitted fluid

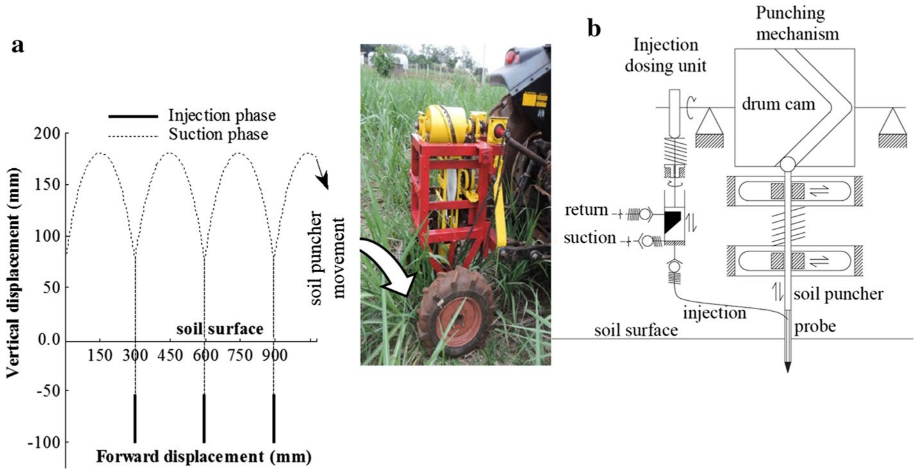

Fig. 1 Working principle for mechanized soil punching combined with injection of liquid fertilizer. **a** Soil punching prototype tested in a sugarcane field (Silva et al. 2017). **b** Injection dosing unit coupled to the soil punching equipment

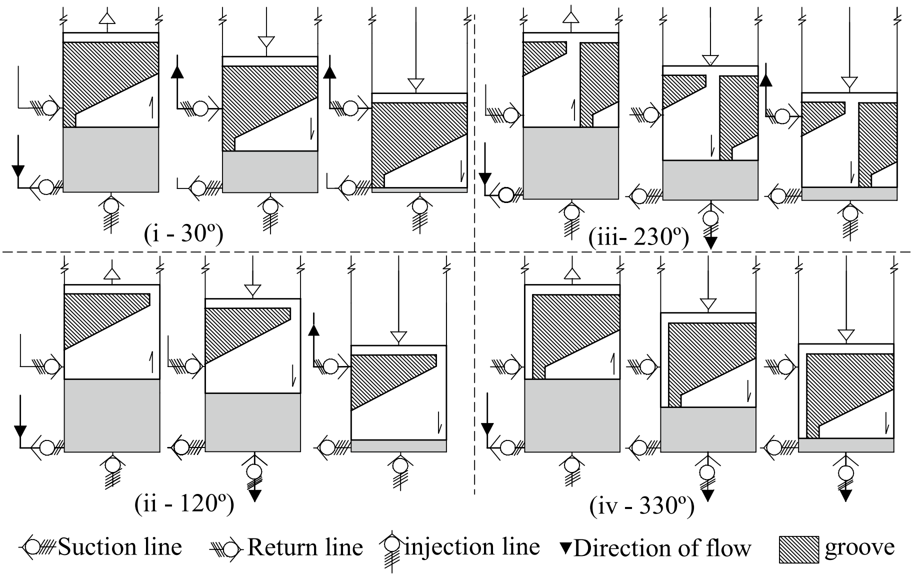

Fig. 2 Working principle that allows variable rate dosage as a function of the radial position of the groove

communication with the hydraulic return according to the radial position of the groove. In addition to the working principle, resistance differences achieved by the check valves were essential for unidirectional flow through the suction, injection and return lines. Inside the chamber, during the period in which the liquid has contact with the return and injection pathways, the liquid flows toward the reservoir due to the lower resistance produced by the cracking pressure of the valve. The working principle is detailed in Fig. 2, as follows:

according to the radial position of the groove, outlet flow may occur only in the direction of the return line due to lower flow resistance (Fig. 2i). Alternatively, the outlet flow is first conducted to the injector, and when fluid communication with the hydraulic return through the groove area occurs, the liquid is deviated to the reservoir (Fig. 2ii). Another radial position can represent a larger applied volume (Fig. 2iii). Additionally, a maximum volume is reached in the radial position, in which the liquid does not have contact with the hydraulic return line (Fig. 2iv).

Liquid injection dosing system represented by a Simulink block diagram

Modeling, simulation and analysis were carried out to assist with specification and sizing, contributing to a better understanding of scenarios that were not covered by the experimental tests. To this end, the operating conditions for nitrogen fertilization in sugarcane fields were taken into account. The model covered parameters such as the forward speed of the machine, fertilizer rate, fertilizer source, soil punching distance and inter-row spacing (Table 1). Additionally, primary dimensions related to the injection piston (diameter and motion amplitude), as well as hydraulic specifications of the check valves (e.g., cracking pressure) and pipelines (diameter), were included. For the injector probe, six 2-mm-diameter orifices around the probe circumference were considered. The orifices are larger than the fertilizer particle size (~0.54 mm) (Boaretto et al. 1991).

Table 1 Essential dimensions and operational parameters applied in the simulation

Operating conditions	
Punching distance	0.3 m cycle^{-1}
Forward speed	0.5–3.5 m s^{-1}
Source	UAN[a]
Crop: sugarcane	
Inter-row spacing	1.5 m
Fertilizer rate	50–180 kg ha^{-1} of N
Piston and chamber	
Diameter	25.4 mm
Section area	5.607×10^{-4} m^2
Amplitude of motion	40 mm
Injector probe	
Probe diameter	15.87 mm
Orifice diameter	2 mm
Number of orifices	6
Total area of orifices	1.885×10^{-5} m^2
Check valves: suction and return	
Cracking pressure	2.2 kPa
Max. cracking pressure	30 kPa
Max. flow	24 l min^{-1}
Check valve: injection	
Cracking pressure	173 kPa
Max. cracking pressure	207 kPa
Max. flow	24 l min^{-1}

[a]Liquid urea–ammonium nitrate

The model diagram (Fig. 3) was developed in the Simulink language, which is linked to the Matlab environment (MathWorks, R2012a, Natick, MA, USA), and the physical and hydraulic characteristics were symbolized by setting blocks. Primarily, a frequency function (repeating sequence block, y) simulated angular velocity in the piston pump shaft. In the block sequence, the cam rotation is transformed by the reciprocating piston motion (embedded block, h). Then, the physical signal is transferred to the piston pump (R port from single-acting hydraulic cylinder, k, l). The piston pump fixed on a rigid frame (mechanical reference, p) performed hydraulic communication (A port) with the suction (d), return (e) and injection (n) pathways. In addition, the hydraulic cylinder was associated with energy dissipation by viscous damping (translational damper, xv), as well as the accumulation and restoration of potential energy (translational spring, i). The primary settings related to the injection piston were section area and reciprocating amplitude.

Analogous to the physical system, the suctioned fluid can be conducted to the injector (o) or returned to the reservoir (a). An orifice with a variable area (ix) simulated the dosage control; this block can conduct a portion of the liquid flow to the return line using a signal function that comes from the injection piston (S port). According to the piston position (axial and radial) during the compression interval, the outlet flow occurs only through the return line (d) because of lower hydraulic resistance. In the hydraulic pathways (d, e and

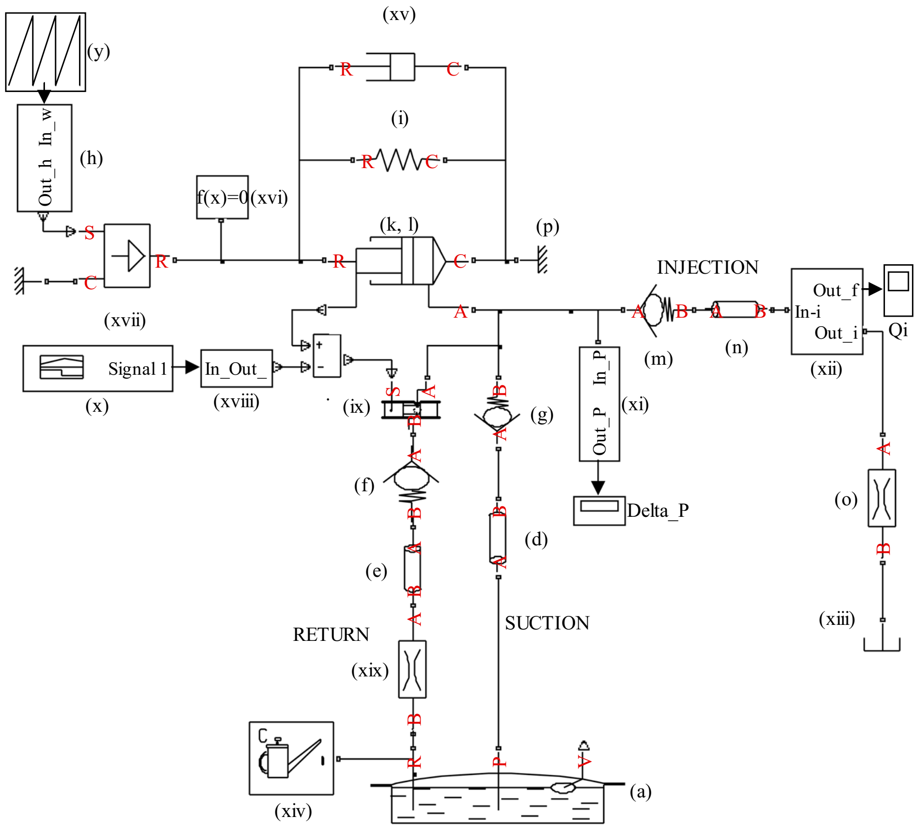

Fig. 3 Injection dosing system modeled as a Simulink block diagram

n), the pipeline parameters were related to the internal diameter, length, wall type (rigid or flexible) and boundary limits of Reynolds number (laminar, transitional and turbulent flow). The check valve block settings (f, g and m), covered characteristics such as the cracking pressure, maximum opening pressure, critical Reynolds number, internal passage area and flow discharge coefficient. An orifice (o) simulated the injector function. For this simulation, inlet flow was linked to the injection pipeline, while the outlet was associated with atmospheric pressure (xviii). The injector settings comprised the total orifice area, flow discharge coefficient and critical Reynolds number. As additional relevant parameters, liquid fertilizer density and viscosity were also considered (hydraulic fluid block, xiv). The analyses focused on outlet flow, hydraulic pressure, applied dosage and hydraulic power. These measurements were registered using blocks from an instrumentation library (xi and xvii).

Injection dosing system descriptions

The injection dosing unit (Fig. 4) was assembled in a metallic frame (p), consisting of rectangular metal plates to ensure rigid support for the chamber (k) and shaft (y) linked to the motor transmission with the cam (h), which is responsible for receiving rotation and transmitting reciprocating motion in the axial piston shaft (l) using a spherical follower (r). This power is also transmitted to the compression spring (i), in which the power is stored as potential energy and released during the suction interval to retract the piston. To prevent misalignment of the reciprocating motion caused by sideway forces, a guide rail (q, t and u) cancels the angular momentum produced by cam transmission (h) concerning the injection piston (l) connected with a square shaft (s). This element passes through a sleeve drilled with a square section (j), in which dosage variation is effected by means of actuation in the radial position of the groove. After dosage adjustment, a threaded element (v) helps ensure the selected angle. Additionally, a threaded seal (w), coupled with a rubber gasket (x), helped to avoid leakage flow in the chamber head. The check valves applied in the suction (g), return (f) and injection (m) pathways were assembled directly in the chamber body (k).

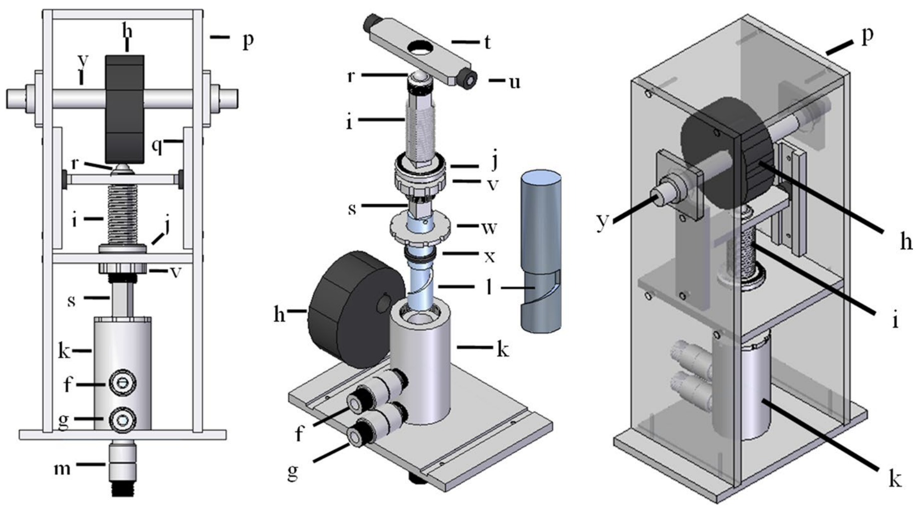

Fig. 4 Liquid dosing injection unit. **a** Front view. **b** Exploded view. **c** Isometric view

After specification (e.g., materials, check valves and rubber gasket), design and manufacturing, the dosing injection unit was assembled on an experimental bench. A three-phase 1.1 kW electric motor (WEG, Jaraguá do Sul, Brazil) was used to drive the dosing injection circuit. The electric motor was connected to a frequency inverter (WEG electric motors, model CFW-08) to control the angular velocity. Velocity variations were measured in the cam shaft (y) using a digital photo-tachometer (Minipa, MDT-2238A model, São Paulo, Brazil). Additionally, a transducer (HBM, Inc., P8AP-20 model, Darmstadt, Germany) was used to measure the hydraulic pressure inside the chamber. The signals acquired by the QuantumX device (HBM, Inc., model MX840A, Darmstadt, Germany) interfaced with a computer via Catman Easy (HBM, Inc., Version 3.4.1, Darmstadt, Germany) and were processed in Matlab. In addition, the injected volume was measured using a graduated receiver, and time was recorded by a chronometer. These samples were used to calculate the average output flow and applied dosage.

Results and discussion

Mechanism for achieving a variable fertilizer rate: the sugarcane case

Sugarcane fields require a nitrogen fertilizer rate ranging from 60 to 150 kg N ha^{-1} (Cantarella and Rossetto 2010). A range of N between 50 and 180 kg ha^{-1} was considered in the hydraulic design to encompass this scenario. In addition, the injection dosing unit was designed considering liquid urea–ammonium nitrate (UAN, 32% of N), a solution with available mineral nitrogen equal to 0.416 kg l^{-1} (Boaretto et al. 1991). Under these conditions, approximately 5–18 ml of UAN per soil punch every 300 mm is needed to meet the application range. Considering another hypothetical simulation under an N fertilizer rate of 100 kg ha^{-1}, a common agronomic recommendation applied in sugarcane fields of the state of São Paulo (Prado and Pancelli 2006), a maximum dosage (~20 ml cycle^{-1}) would be required to apply liquid urea (concentration equal to 0.22 kg l^{-1} of N). According to the nitrogen source, lower concentrations can reduce the size capacity of the fertilizer range. Fundamentally, more simulations can lead to a better design according to real scenarios.

In piston design, when the radial angles between 0° and 60° are aligned with the hydraulic return line, the groove allows outlet flow toward the reservoir during the entire compression interval. For this condition, the liquid flows to the reservoir because of the lower resistance achieved by the cracking pressure of the check valve (2.2 kPa, Table 1), which is approximately 70 times less than the cracking pressure linked to the valve from injection (172 kPa). Then, between 60° and 300°, dosage increments applied in the injection pathway were designed as a function of the groove angle, aligned with the return line. The maximum dosage (~20 ml cycle^{-1}) is applied between 300° and 360°. Within this interval, fluid does not have contact with the hydraulic return pathway.

Essentially, liquid suction effectiveness and primary dimensions (Table 1) determine the applied volume per cycle. Through experimental measurements, the system reached an approximately linear range between 5 and 18 ml cycle^{-1}, which is similar to the required, ideal conditions (Fig. 5). This result indicates an adequate quality to achieve a variable fertilizer rate according to the agronomic recommendations. Variable rate technology in traditional systems generally uses a servo valve to control liquid fertilizer flow through the injection line; between the injection pump and servo valve, a three-way valve is used,

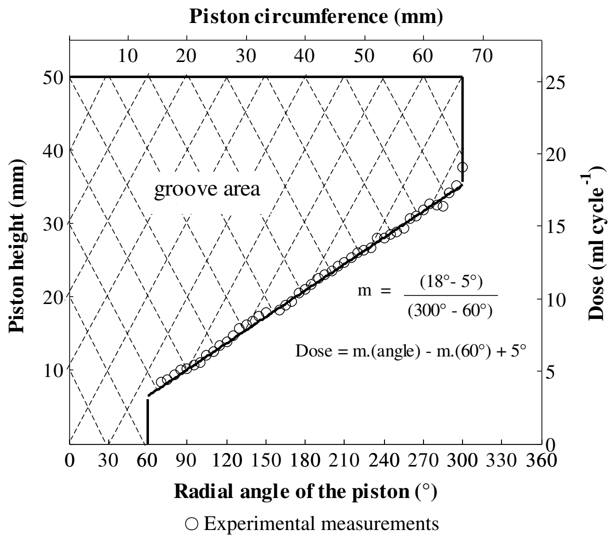

Fig. 5 Groove diagram designed for the injection piston that allows dosage control, compared with experimental measurements on the laboratory bench

through which outlet flow returns to the reservoir. Here, the injection dosing unit simplified this function, which is an advantage for dosage control.

Hydraulic pressure characteristics

Some characteristics of hydraulic pressure in the piston chamber were highlighted in the operating cycle (Fig. 6). Between the interval of 0 and 3π/2 rad, small and negative values were due to liquid suction linked to the soil puncher movement above the ground. In the sequence, the pressure increases along the injection phase up to 2π rad, including soil punching to a depth of approximately 50–100 mm. The pressure peaks were associated

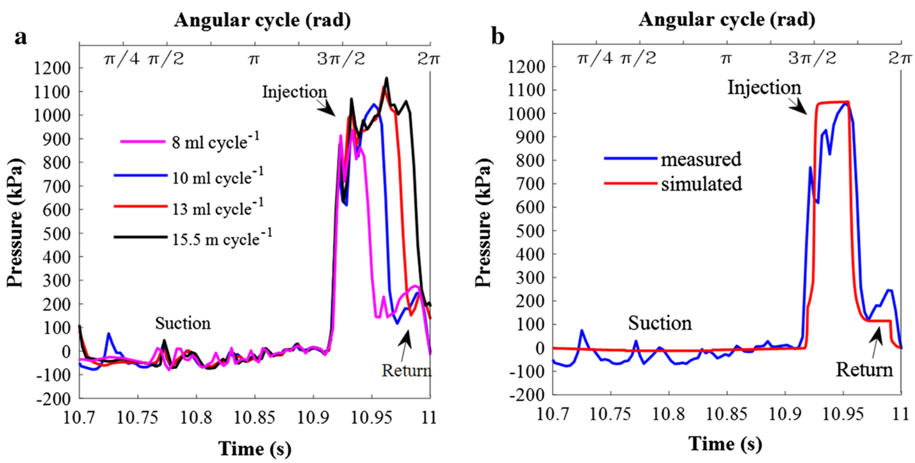

Fig. 6 Hydraulic pressure in the piston pump, under conditions equivalent to 1 m s^{-1} of forward speed. **a** Measurements from one operating cycle. **b** Experimental measurements contrasted with simulation results

with flow resistance caused by the hydraulic elements, such as the cracking pressure of the check valve (~170 kPa), pipelines, the pressure drop across the injector orifices (~625 kPa) and fluid inertia resistance linked to the pressure drop caused by kinetic energy loss (~250 kPa). The power demand is essentially dependent on the hydraulic pressure and outlet flow. In addition, hydraulic power is not constant, and maximum values peak at compression intervals. Additionally, the pressure measurements (Fig. 6a) revealed the communication moment with the return line. The period included in the compression interval is characterized by an abrupt pressure drop associated with lower hydraulic resistance in the return line.

In general, the experimental measurements were similar to the simulation curves (Fig. 6b). These comparisons give credence to the liquid injection estimates for nitrogen fertilization. In these simulations and analyses, it was perceived that flow resistance through the injection orifices represented the most significant contribution to the pressure peaks measured inside the piston chamber. Based on the steady orifice formulation, the differential pressure is associated mainly with liquid velocity. The outlet flow level can also produce changes in discharge flow efficiency (Knutson and Van de Ven 2016). In hydraulic design, a constant dimensionless value of 0.6 is commonly assumed as the discharge coefficient, especially when applied to the orifice plates, Venturi pipes and nozzles (NBR-ISO-5167 1994). However, measurements suggest lower indices, between 0.3 and 0.5 (Knutson and Van de Ven 2016). The measurements indicated a discharge coefficient of approximately 0.4; this parameter is important for improving liquid injection estimates.

The experimental measurements also revealed some details related to dynamic characteristics that were not covered by the modeling. As an example, during outlet flow to the reservoir, an overshoot occurs after pressure decay (highlighted on curve of 8 ml cycle^{-1}, Fig. 6a). This transient overshoot was associated with water hammer emergence from the check valve due to rapid decreases in hydraulic pressure and fluid velocity (Kaliatka et al. 2014; Karney and Simpson 2007; Meng et al. 2012; Xu et al. 2011). This significant pressure can produce negative results, such as partial leakage flow across the injection line during flow return to the reservoir.

Simulations and analysis of liquid fertilizer injection

Essentially, the applied dosage is a function of the groove position related to the hydraulic return (Fig. 7a). The forward velocity range produced few dosage changes when fixed at a radial angle. However, velocity increments produced hydraulic pressure elevation (Fig. 7b), with consequences in the check valves (opening and closing process), especially at lower dosage levels, which are associated with larger common intervals and communication between the return and injection pathways. These characteristics during return flow may favor some leakage along the injection line. Even so, the applied dosage presented a consistent pattern for the radial angle of the groove, mainly when taking into account a narrow velocity range.

In general, an approximately constant forward speed is applied during mechanized nitrogen fertilization. This condition helps ensure smaller variations in hydraulic pressure; as a consequence, this approach also reduces changes in the selected dosage level. In the experimental measurements evaluated with four replicates, with a fixed forward speed, the doses led to a small coefficient of variation, below 2%. For other technologies, such as fertilizer broadcasting, the coefficient of variation can reach much higher values, between

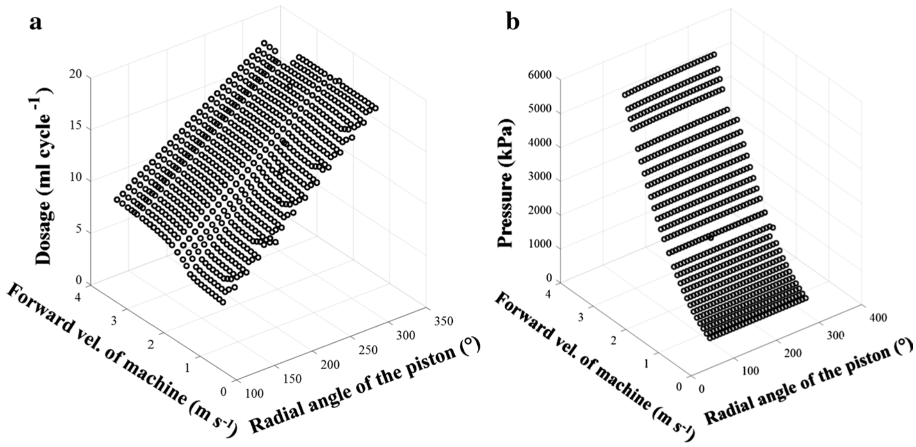

Fig. 7 Simulations performed for nitrogen fertilization in sugarcane, considering **a** the applied dosage and **b** the hydraulic pressure in the piston pump

20 and 35% (Campbell et al. 2015; Fulton et al. 2001; Virk et al. 2013). Therefore, the proposed dosing injection system has the potential to improve application quality.

Although the dosage increased according to the radial position of the piston (60°–300°), the pressure peaks were maintained practically unaltered under constant forward velocity (Fig. 7b). In addition, the velocity increase caused an exponential pressure elevation, which was propagated in the injection line under proportional jet velocity, including the outlet flow into the soil. These results were associated with non-linearity over the injection timing as a function of forward velocity. When higher velocities were used, the injection timing decreased, trending toward zero. Similarly, the soil punching timing decreased under the same rate. Thus, a velocity increase leads to lower injection timing associated with proportional fluid compression, which produces direct influences on the fluid pressure and flow. Further, more available power is required to operate under these circumstances.

A critical scenario for the proposed liquid injection occurs when compared to the mechanized placement of fertilizer on the surface. This machinery model can operate at a forward velocity of approximately 3.5 m s^{-1} for nitrogen fertilization in sugarcane fields. When the injection dosing system is applied at that forward velocity, the pressure peak was estimated at 7700 kPa, with instantaneous flow equal to 55 l min^{-1}. This result surpasses the nominal physical specification (24 l min^{-1}, Table 1) and demands a higher power per sugarcane row (7.2 kW). On the other hand, the mechanized placement of fertilizer on the soil surface requires less complex components (e.g., centrifugal pumps). In addition, the systems can supply more than one spray nozzle per boom section, due to the low hydraulic power demand per row, which allows a larger effective field capacity. However, N fertilizer placement on the surface of crop residues decreases the nitrogen fertilizer efficiency in sugarcane fields (Castro et al. 2017; Otto et al. 2016; Prasertsak et al. 2002). In a recent comparison of N fertilizer placement effects on sugarcane yield, Silva et al. (2017) showed that point placement was more effective than surface application (98 Mg ha^{-1} vs. 91 Mg ha^{-1} yield). The result was associated with mineral N availability for plant uptake achieved by liquid fertilizer injection near the cane roots.

During mechanized fertilizer placement in narrow trenches, effective field capacity is obtained with simultaneous application to two sugarcane rows, at a forward speed of ~ 1.5 m s^{-1}. Taking into account an equivalent process using the injection dosing system, the hydraulic pressure reaches 1500 kPa with an instantaneous flow of 23 l min^{-1}. This condition required an estimated hydraulic power of 0.6 kW per sugarcane row, a value that is considered compatible with common sources of power transmission used in agricultural machinery (power take-off and electric and hydraulic motors). Additionally, liquid fertilizer velocity through the injection orifices produces a wet bulb around the placement point, which can help with mineral N diffusion for plant uptake. Liquid penetration occurs due to jet pressure, which is sufficient to locally reduce and crack the soil binding mechanisms (Niemoeller et al. 2011). Technologies developed to overcome difficulties in the placement of fertilizer into the soil are relevant to plant nutrition and environmental protection (Liu et al. 2015). The principle of liquid fertilizer injection was previously presented by Baker et al. (1989) in a technology named the “spoke wheel”, which is especially dedicated to maize nutrition. However, clogging with soil (influence in dosage uniformity) and soil resistance (application depth) were some of the restrictions for widespread adoption.

Additionally, other systems have been described in the literature for liquid fertilizer injection into the soil subsurface. Nyord et al. (2008) compared three application techniques, including the system proposed by Baker et al. (1989) and a high-pressure injector developed by their own group. In general, liquid penetration into the soil was classified as the major limiting factor. The authors conclude that the depth reached (only 20 mm) was not sufficient to reduce ammonia volatilization; however, both systems showed higher crop yields when compared to surface application. The high-pressure jet injection technology was also explored by Niemoeller et al. (2011). The author found that fertilizer injection capacity depended on soil type and average soil moisture; however, this study showed that the injection of liquid fertilizer has the potential to reduce ammonia volatilization and protect plants. Here, the proposed system presents some advantages over the limitations of these systems. Further, the proposed system can inject the deepest fertilizer, up to 100 mm, which is sufficient to overcome the problem of ammonia volatilization; in addition, this system is less dependent on physical parameters of the soil, such as moisture, type and penetration resistance.

The mechanism for liquid injection through soil punching can also be adapted for nutrient supply in wetland rice. Analogous to nitrogen fertilization in sugarcane, nitrogen placement on the surface of paddy fields is a typical practice. In rice fields, side dressing and broadcasting application are associated with ammonia emission, ammonium dissolved in floodwater (NH_4^+–N), and alterations of water pH (Liu et al. 2015). As proved previously, deep placement of nitrogen fertilizer reduces ammonia volatilization and increases nitrogen use efficiency in paddy fields (Bautista et al. 2001; Liu et al. 2015). In addition, floodwater depth, clogging and permanent crop damage are difficulties associated with continuous fertilizer incorporation. Under these conditions, the injection dosing system for site-specific management of fertilizer represents an appropriate solution.

Conclusions

An injection dosing system for site-specific management was conceptualized using conservation tillage practices. The mechanism can provide variable rate liquid fertilizer at placement into the soil. The liquid fertilizer is injected during mechanized soil punching at a depth of 50–100 mm (an appropriate depth for decreasing N fertilizer losses and providing nutrients near plant roots). Soil punching can access most easily the subsurface of the soil through perforation of the crop residue layer, with minimal disturbance. Additionally, the injection dosing unit can provide the liquid dosage in a representative range (5.0–18 ml cycle^{-1}), which is appropriate for application according to agronomic recommendations and is compatible with plant demand. These characteristics follow better management principles for nutrient stewardship, which are especially relevant for nitrogen fertilization in growing crops, such as sugarcane fields.

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