A FEASIBILITY STUDY OF DEVELOPING DIRECT INJECTION SPRAYING TECHNOLOGY FOR SMALL SCALE FARMS

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ABSRACT

The present study focuses on designing hydraulic scheme and process control system for small direct injection sprayer equipped with five meters' boom (10 tip nozzles) based on DC electrical energy supply. A numerical model was developed by using finite volume method to study dynamic of concentration change process and to optimize the hydraulic boom design required to overcome lag transport problem related to real time application. The schemes of serial and parallel boom layouts were studied to obtain minimal lag transport for chemical concentration change process. The process control system was modelled in Matlab-Simulink^{TM}, and a laboratory test bench was implemented with a PID (Proportional Integral Derivative) feedback control for evaluating the performance of the constant carrier flow and the variable total flow strategies.

The results of the hydraulic modelling of the serial boom layout showed that 6 mm boom diameter gave a satisfying performance in term of application uniformity (up to 97%) and lag transport along nozzles (from 0.8 to 1.5 s). The prospection of parallel scheme by feeding individually nozzles gave an even reduced lag transport (2 s) along the boom (diameter of 4 mm).

The modelling of constant carrier flow control strategy showed a lag time of 2.5 s for the step speed change of 0.6 to 1.2 m/s at constant pressure of 2 bars. The total flow control strategy showed the advantage of reducing lag transport from 4 to 2.3 s when speed varied from 0.6 to 1.2 m/s in accordance with operating pressure (from 1 to 3 bars). The experimental tests showed the importance of varying carrier flow rate to improve the controller dynamic in comparison to the constant carrier flow control.

INTRODUCTION

Development of direct injection sprayer (DIS) to apply variable rate based on actual ground speed can be of great importance for providing small farms with accurate chemical application method and limiting environmental risk. Direct injection is an electronically controlled system in which a pesticide is injected into a carrier. Application rate management is a real time operation achieved by a controller that maintains spatially an uniform chemical application independently of working speed variation.

Advantage of using small sprayers equipped with an integrated direct injection system result in keeping separately the chemical and the carrier from each other, so that only a required amount of pesticide is diluted in the carrier. In this regard, the problems of washing water, left-over tank mixtures and exposure of applicators during mixing and loading, are systemically avoided (Landers, 1999).

Performance of direct injection sprayer depends mainly on the hydraulic design to limit lag transport and the process control strategy to optimize system dynamics to overcome time delay. The optimal design does not only to maintain an even application rate between nozzles but also to change applied chemical concentration in accordance with varying working speed. The concentration change should be done within a short lag time to keep chemical application error at admissible level of 5 % [Miller and Smith, 1992; Steward et al., 2000].

Improvement of hydraulic performance of spraying system constitutes the key for precisely applying variable chemical rate. It depends mainly of hydraulic scheme to take advantage of flow hydrodynamic behaviour to overcome transport lag as determinant factor for obtaining fast response time.

Computation of optimal hydraulic scheme of DIS search for speeding up the response of system that can be affected by lag transport. There is a compromising point to search between the process of concentration transport and friction loss. In fact, Maximising flow transport can dispose the spraying system of a fast response time and a favourable mixture quality due to turbulent flow regime. However, friction loss tends to create a pressure drop along boom as flow increases and induces spraying miss uniformity (Hloben, 2007; El Aissaoui et al, 2009).

Chemical formulation presents also an effect on hydraulic performance when applied mixture tends to be viscous. The change in flow dynamic due to viscosity can affect the system response and applied mixture tends to be not uniform. The chemical formulations bought in the market have a viscosity range varying from 1 mPa.s to 1000 mPa.s but viscosities of most chemical formulations used in agriculture are less than 100 mPa.s (Zhu et al, 1998).

Lag transport and mixing quality are the main requirements needed for DIS to carry out real time chemical application, and performance of rolling small direct injection sprayer handled by operator depends on its dynamic behaviour to obtain fast response for concentration change process. Several authors approached lag transport in DIS equipped of injection point at pump or boom level and found delay times situated between 4 s to 55 s (Budwig et al, 1988, Tompkins et al., 1990; Sudduth et al., 1995; Koo et al., 1998, Zhu et al., 1998; Angluned and Ayers, 2003; Hloben, 2007). The objective of the present study consisted in approaching the influence of hydraulic design and process control system on the dynamic performance of direct injection system.

MATERIAL AND METHODS

The study of sprayer hydraulic configuration was done by developing a computation model based on control volume method to characterise mixture flow dynamic in direct injection spraying boom for nozzles disposition of serial and parallel feeding schemes. Two cases of serial and parallel boom layouts were studied for assessing model computation (Fig. 1 and Fig. 2).

A DIS test bench laboratory was mounted with main diaphragm pump (Flojet of Sherflo, 24V DC, 10 L/mn at 2.8 bars), and peristaltic pump (Marlow Watson^{TM} 400D/E, two channels, 38 mL/mn (x 2)) to simulate chemical injection by using fluorescein tracer at upstream point of the main pump. Diaphragm and peristaltic pumps were actuated by PWM modules (2020S of CJ Controls LTD). Pressure gradient was measured along boom by using two sensors (Sensorthechnics^{TM} CTE 8005GY7, Pmax = 5 bars, non-linearity = 0.1, hysteresis = 0.015) mounted in upstream and downstream boom levels. Lag transport was approached by using fluorometric sensor at each tip nozzle level. Five sensors were designed and calibrated to sense fluorescein transmittance at 520 µm at the level of each nozzle body (El Aissaoui et al., 2007).

Characterization of lag transport for both serial and parallel boom layout was done on the basis of dead time, time constant and rise time. The first time is delay from the starting in injection point to the starting of concentration response at tip nozzle level. It depends on dead volume and flow speed along feeding line. The second one is time required to reach 63.2 % of concentration change. The third one is time needed for the concentration process to make change from 10 to 90 %.

The serial boom layout was made from commercial copper tubing sections (diameter = 6 mm, length = 500mm and roughness = 2 µm) connected to nozzles body via tee junctions. The parallel boom layout was done by using quick connect flexible (Festo^{TM}, d = 4mm, roughness~ 2 µm) to attach each nozzle body to the pump (Fig. 2).

The study of the process controller was done by first modelling the system in Matlab-Simulink^{TM} and after that implementing it in laboratory for evaluating performance of constant carrier flow and variable total flow control strategies. The control strategies were based on PID control loops to adjust concentration injection ratio accordingly to the operating pressure (constant or variable carrier control) and simulated operating speed (different step change). A virtual instrument (LabVIEW^{TM}) was implemented to acquire data via DAQ NI-USB6251 at sampling frequency of 10 Hz and after that, the constant carrier flow control strategy was implemented on PLC for test in laboratory on the basis of data of real operating speed profile.

The carrier and injection flow rate processes were approached as a first order system with dead time $G_p(s) = Ke^{-sto}/(\tau s+1)$ (Guzmán et al., 2004). The dead time is due mainly to dead volume of carrier pump and boom layout. The controller commands the diaphragm pump on the basis of the pressure feedback sensed at tip nozzle level. The metering control loop was implemented to command voltage (U_c) of the metering pump within the magnitude of [1.5 V to 4.7 V] as a response for speed change within the magnitude of [0.5 m/s to 1.5 m/s].

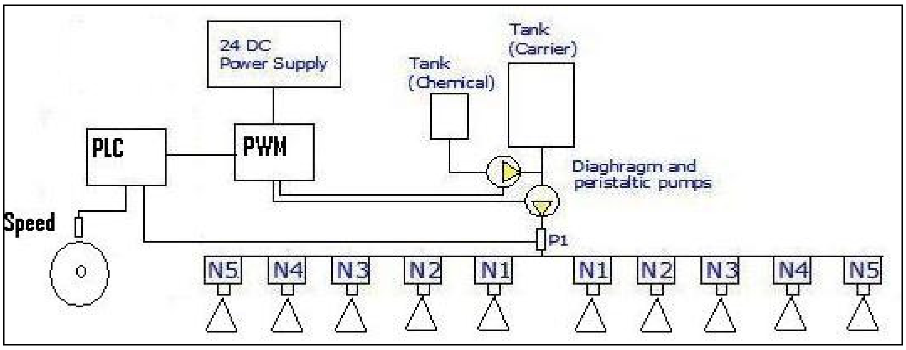

Fig. 1 Electrical DIS scheme based on conventional serial boom layout

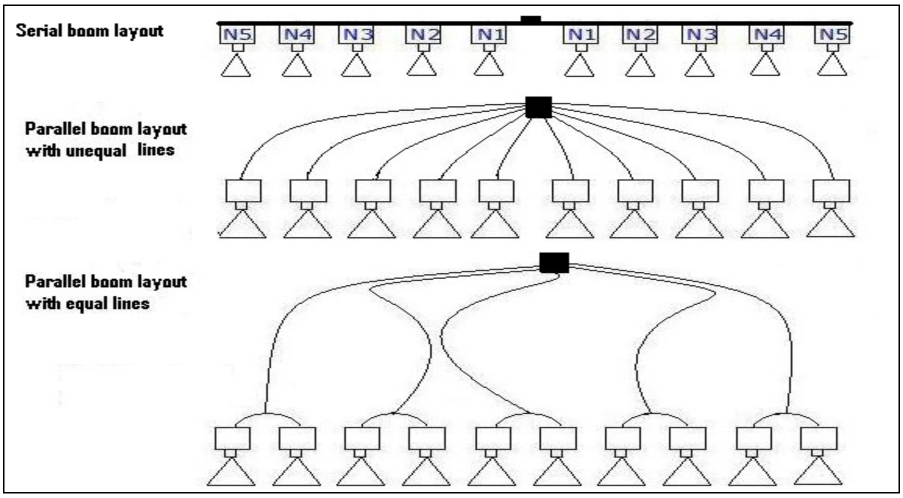

Fig. 2 Serial and parallel boom layouts

RESULTS AND DISCUSSION

Hydraulic study of serial boom layout

Three boom diameters of 5, 6 and 8 mm were simulated by the model. The simulation results showed the effects of diameter on lag transport and of pressure drop on application uniformity. Reduced boom diameter (case of 5 mm) can improve lag transport (1 s) but the application uniformity (93 %) tends to be poor along boom because of pressure decrease. The diameter boom of 6 mm (application uniformity of 97 % and lag transport of 1.5 s) showed relatively a satisfying performance to use serial boom configuration for direct injection spraying (Fig. 3).

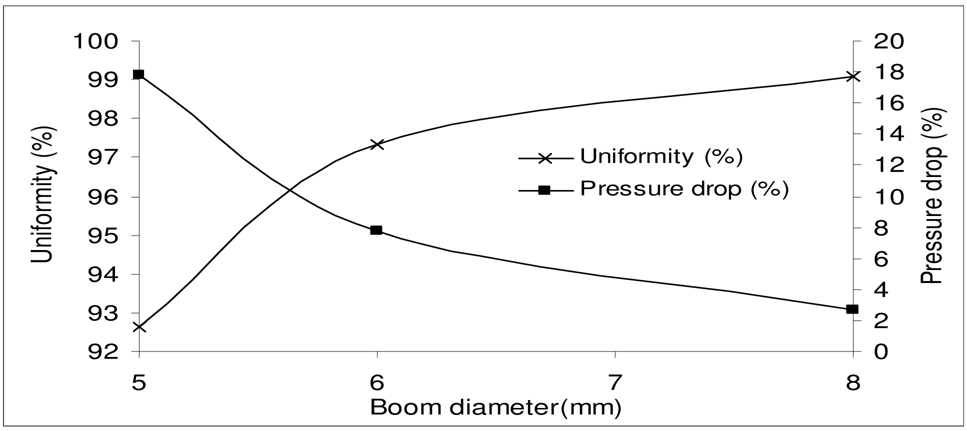

Fig. 3 Effect of boom diameter on application uniformity and pressure drop over five nozzles in serial scheme.

The transport lag profile along serial boom layout showed that the delay time allowed to each nozzle tends to increase from 9 % (nozzle 1) to 43 % (nozzle 5). The lag transport of the fourth and fifth nozzles took 65 % of total lag due to low flow speed occurring at the boom end. This lag transport variability affected not only longitudinal application uniformity but also the transversal one.

The study of Reynolds number profile along the boom pointed out the advantage of reducing boom diameter (6 mm) for improving mixing quality as the flow was kept turbulent (Re > 3000). The simulated results showed also that viscosity could significantly affect flow regime by decreasing Reynolds number. In fact, the mixing process cannot be improved as the flow stayed laminar. The viscosity effect was non significant even though we varied its intensity from 10^{-6} to 10^{-5} m^2/s to affect boom flow uniformity (less than 1 %).

Hydraulic study of parallel boom layout

Choosing small boom diameter (< 6 mm) can be important to improve hydraulic lag transport but it could not be efficient for use in serial boom scheme as shown before. The use of parallel boom scheme based on feeding separately one or two nozzles can be optimal to overcome lag transport problem without affecting application uniformity related to pressure drop.

The study of parallel boom layout with variable feeding nozzles lines can be of importance to improve the process of concentration change as the flow rate was constant between nozzles. However, the lag transport depended on the length of each nozzle feeding line according to its place on the boom. Independently of feeding line diameter, variable line length between nozzles induced variable delay time for the concentration process change (Fig. 4).

Evaluation of pressure drop on the parallel boom layout was done between the pump output and the nearest nozzle 1 (0.5 m) and the farthest nozzle 5 (2.5 m). The pressure gradient between the nozzles 1 and 5 was about 7 %. The lag transport of the five nozzles mounted in serial layout was evaluated experimentally to 5 s (from injection point to the fifth tip nozzle). Figure 4a showed a dead time change between nozzles to move upward from 0.3 s (Nozzle 1) to 1.8 s (Nozzle 5). The time constant changed from 1 s (Nozzle 1) to 1.3 s (Nozzle 5). The rise time increased slightly to form different S-shaped curves. The total lag transport of the five parallel nozzles kept around 4 s. Dead time stepped constantly from 0.4 s (Nozzle 1) to 2 s (Nozzle 5). The time constant was the same (0.9 s) for the five nozzles. The rise time took the same value of 1.2 s for the five nozzles, forming similar S-shaped curves (Fig. 4)

Parallel boom layout with equal feeding line is of importance to solve the problem of variable dead time between nozzles and avoid lateral misapplication uniformity. Furthermore, lag transport can be reduced by adapting parallel boom layout to serve each pair of nozzles from one feeding line (Fig. 2). In fact, test of this layout showed that the dead time keeps constantly around 0.8 s for all nozzles. The time needed by concentration change evaluated at 2 s (from pump output to nozzle tip). However, the occurring pressure drop became important to be around 10 %.

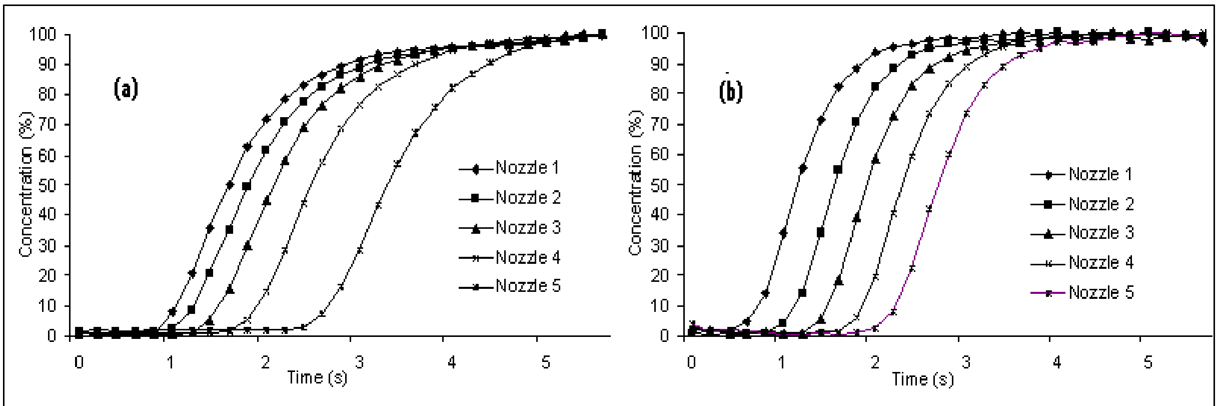

Fig. 4 Concentration change process in serial (a) and parallel (b) boom layouts

Study of process control system

The constant carrier flow control strategy was modelled for operating pressure of 2 bars (Fig. 5). Results showed a delayed response in nozzle's concentration of less than 3 s for 0.6-1.2 m/s step change. The steps generated experimentally showed the same transport lag and control system behaviour. Even though chemical injection upstream to pressuring pump has been used for improving mixing quality, the resulting lag time shows a comparative performance of 2.5 s found by Rockwell and Ayers (1996) by injecting the active ingredient directly into the nozzle housing. Anglund and Ayers (2003) evaluated the performance of direct injection sprayer for variable rate application and found a lag time varying from 15 to 55 s due to carrier flow rate variation. The constant carrier flow control can be effective when the frequency of operating speed change is not higher (< 0.5 m/s^2) to affect the control dynamic for overcoming the problem of lag transport. The overshooting of the carrier flow can be of great concern to speed up the control of nozzle concentration and continuously maintain the recommended TAR variability within ±5% [Steward et al., 2000].

The modelling of total flow control strategy by varying operating pressure from 1 to 3 bars showed that lag transport decreased from 4 to 2.3 s as speed increase from 0.6 to 1.2 m/s. The experimental test showed that the control response to ramp and step solicitations was improved in comparison to the constant carrier flow control. The lag transport compensation due to pressure increasing can be of great concern with the use of nozzles operating at the large pressure range. However, the performance and stability of varying pressure process keeps conditioned by the softness of operating speed change. The reliability and endurance of carrier flow pump are too of great importance to maintain the control performance and system durability.

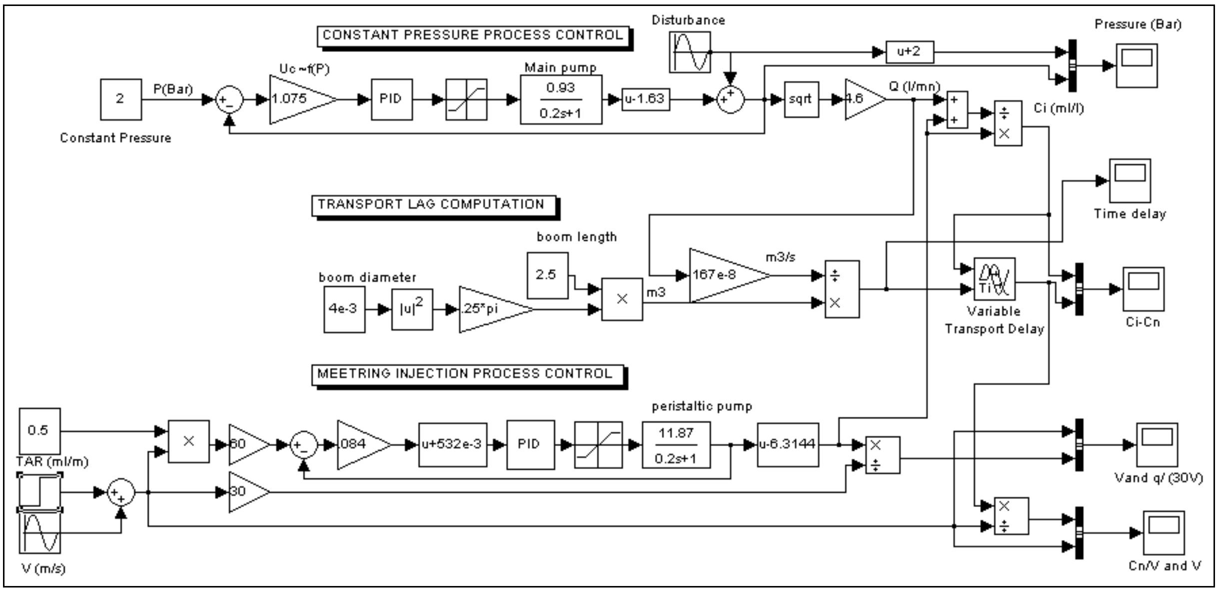

Fig. 5 Process control model of DIS (Matlab-Simulink^{TM})

CONCLUSION

The study of hydraulic boom configuration showed that lag transport can be reduced to 2 s. According to existing performance (> 4 s), this value is of great importance to improve dynamic of direct injection system for variable rate application. Evaluation of the two process control strategies showed the technical feasibility of the direct injection technology to be mounted on pushed or pulled rolling sprayer for small scale farms. The constant carrier flow control can be relatively the simplest and affordable solution to be used in developing country regarding to its easy implementation, and possibility of its adaptation to existing sprayer. However, instantaneous speed variation of operator should be done within 0.5 m/s^2 for the system stability. The Implementation of control system to induce instantaneous flow rate overshooting help to overcome lag transport and enforce more the stability of system. Otherwise, the response of system can be more improved by using total carrier flow control strategy.

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