Development of an Optical Sensor to Measure Direct Injection Spraying System Performance

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Abstract

Evaluation of direct injection sprayer's performance is an important step for a successful direct injection sprayer technology development. A low-cost optical sensor was developed to characterize direct injection system response by dynamic measurement of fluorescent dye concentration. The method is based on sensing the fluorescence of mixture by the light-to-voltage converter equipped with integral optical green filter TSLG257. The dye is excited by one blue light LED HLMP-CB15 (emission band of 472 nm ± 32). The light transmittance was measured by the converter in two on-line positions to LED; the emitter and transmitter placed longitudinally at 45° angle and transversally at 90° angle to flow line. The measurement of transmittance for concentrations between 0 to 10 mg/l showed that the trend is linear for concentrations under 2.5 mg/l (R^2 > 99%).The results showed that the offset for longitudinal measurements is bigger than for the transversal ones (about 600%) because of the direct interception of the light by the converter. The highest sensitivity is related to the transversal 90° position transmittance. The amplification of the excitation power of the LED by varying current supply between 50% and 100% gave a proportional increase of the sensitivity without affecting the linearity. Test results of sensor showed that it can be used to calibrate direct injection system accurately and to characterize the performance of the system for upstream and downstream injection location.

Key words: direct injection, sensor, fluorescent dye, spray, pesticide

Introduction

Improvement of pesticide application and reduction of environmental contamination require that quantity and quality of active ingredient sprayed on target and off-target should be sensed accurately and easily with practicable methods. Many laboratory and field tests have been conducted using colorimetric and/or fluorometric tracers to measure spray deposition, spray penetration, coverage, drift and to evaluate direct injection sprayers performance [1, 3 trough 13].

In most direct injection sprayers, water is pumped at constant flow rate to the spray nozzles and the concentrated chemical is metered and injected proportionally to travel speed. The big problem associated with injection spray technique relates to lag time, which can cause

improper application rates with rapid changes of travel speed. To evaluate this problem, it is necessary to develop accurate method for measuring lag time.

Several steady state and sampling methods have been used to determine mixture concentration evolution in the boom and at the nozzles by time to evaluate dynamic performance of sprayers. Larson & al (1982) used a colorimetric method to determine spray patterns. Cho & al (1985), Tompkins & al (1990), Antuniassi & al (2002) and Hloben & al (2003) used salted water as a conductmetric method for sensing concentration of injected solution to evaluate performance of direct injection sprayers. Koo & al (1987) connected a fluorometer to a spray boom to measure fluorescent dye (Rhodamine) concentration. Rockwell and Ayres (1996) and Sumner & al (2000) used fluorescent dye string collectors to evaluate uniformity and lag time across the nozzle spray pattern. Zhu & al (1998) developed a turntable laboratory system to measure lag time to achieve desired spray concentration by changing travel speed and measuring spray mixture uniformity as function of time.

However, the previously cited methods have apparent disadvantages and systematic error when mixture concentration sampling is used to determine statically the accuracy of direct injection system. Some of these methods are very consuming in time and labor to complete sample analysis. Furthermore, accuracy of some methods for measuring the time required for the proper mixture to be sprayed from nozzles is questionable due to their slow response to concentration changes [12].

The objective of this research is to develop an optical on-line sensor for measuring fluorescein concentration and evaluating performance of direct injection systems in laboratory and field conditions.

Fluorescein proprieties

Fluorescein ($C_{20}H_{10}Na_2O_5$) has 70% dye and 30% sodium salt content. The excitation and emission peaks are located respectively at 494 nm and 516 nm (Fig.1). The quantum photons yield Ø (emission intensity/reception intensity) is about 90%. The extinction coefficient (ε) representing absorption probability of one molecule is about 80 000 $cm^{-1}.M^{-1}$. The fluorescence intensity or brightness (ε x Ø) is about 72 000 $cm^{-1}.M^{-1}$ [2].The fluorescence life time of excited state is less than 3 ns. This short time provide fluorescein of high dynamic response time to sense instantaneously the transmittance related to variable concentration flow on-line.

The fluorescein tracer has advantage of high sensitivity, low cost, no environmental risk and user safety to quantify pesticide concentration. In fact, it is widely used for measuring spray deposition and uniformity in the field and for evaluating direct injection sprayers performance regarding to accuracy and delay response of rate application. However, the measuring

accuracy is dependent of the stability of fluorescence during experiment due to photodegradation under sunlight, pH and temperature condition [14].

Zhu et al (2004) investigated fluorescein photodegradation exposed to direct sunlight, under artificial shade, and in dark room from 0 to 2 hours. They found that fluorescence peaks sensed by liquid chromatography analyser kept consistent in the dark condition for 2 hours. However, peaks heights for samples under direct sunlight and shade decreased in the first half hour and then tended to become stable. They used the photodegradation calibration ratio as correction to evaluate spray deposits at the canopies levels. To minimise measurement errors due to exposure to sunlight, Pergher & al (1995) performed field trials to evaluate spray application rate and airflow rate in vineyard by using florescent tracer in the early morning and in the evening in order to solve photodegradation problem.

Zhu & al (2005) sensed the stability of fluorescent intensity under different pH values for five fluorescent tracers (Fluorescein, Pyranine, Tinopal, BSF and Eosin) commonly used to assess spray deposit quantity and off-target loss. Results showed that fluorescence of Pyranine was the most sensitive to the solution pH conditions followed by fluorescein and Tinopal. The fluorescence of Fluorescein increased 1.3 times, Tinopal 1.25 times, and Pyranine 3.0 times as the pH value increased from 6.9 to 8.4, but it became nearly constant when pH value was greater than 8.4.
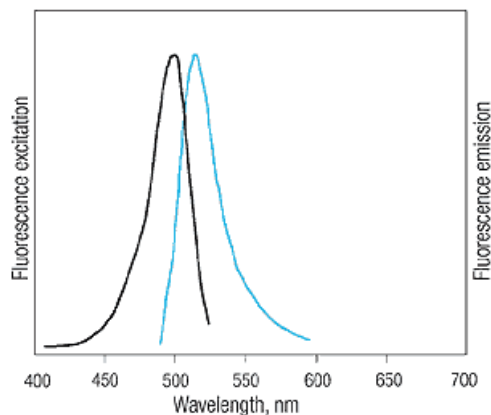

Fig.1: Fluorescein wavelength chart

Preliminary design and test of sensor

The developed sensor (fig.2) consists of an emitter and a receptor of light transmittance. The blue light LED HLMP-CB15 of 472 nm ± 32 emission band (Agilent Technologies[TM]) is used to excite fluorescein mixture and the light-to-voltage converter equipped with integral optical green filter TSLG257 (TAOS[TM]) is used to receive the transmittance of excited mixture. The two components are placed along the flow line on 3/8 or 1/2 inch tubing for easy integration on existing sprayer's hydraulic circuitry.

In the preliminary investigation, the test was conducted with the first design in order to choose the best emission wavelength and transmittance position. The transmittance voltage was measured for different solution concentration with a portable multimeter (HP 34401A).
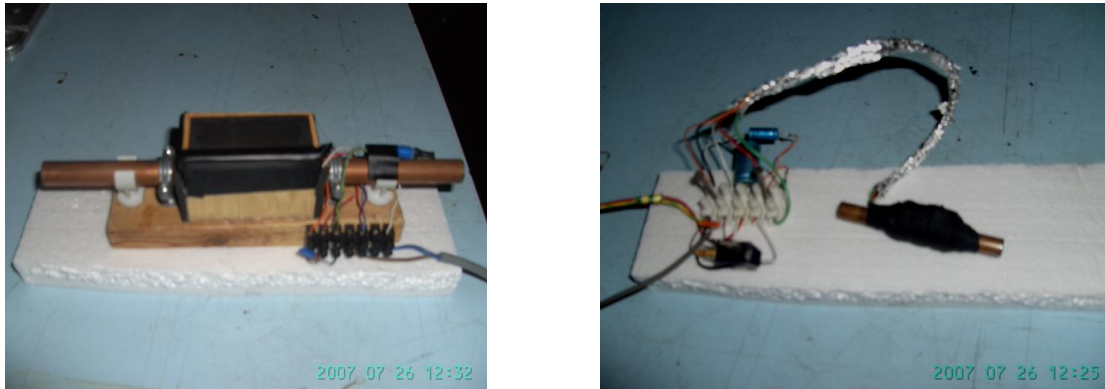

Fig.2: First design (1/2 inch) and final design (3/8 inch) of developed sensor

Emitter LED of two different wave lengths (430 nm and 470 nm) were tested for tow emitter-receptor configurations of longitudinal at 45° angle and transversal at 90° angle positions (fig 3a). The fluorescence sensed on flow line was investigated to compare voltage and slope response. Furthermore, two excitation powers were tested by changing current supply of LED from 50% to 100% of nominal value. Results showed that the 470 nm LED gave highest sensitivity to the fluorescein concentration at the cost of the higher offset (Fig 3b). The comparison between longitudinally 45° and transversally 90° transmittance positions showed the highest voltage offset for the first one and the highest sensitivity (>30 times) for the second one. Therefore, the transversal design was jugged the best one because of highest sensitivity, lowest interference noise and best ability to sense mixture deeply. However, the transmittance for the longitudinal 45° position could be the most effective for sensing tangentially fluorescence of opaque mixture. The amplification of LED current supply by two showed a proportional increase on the slope without affecting the linearity.
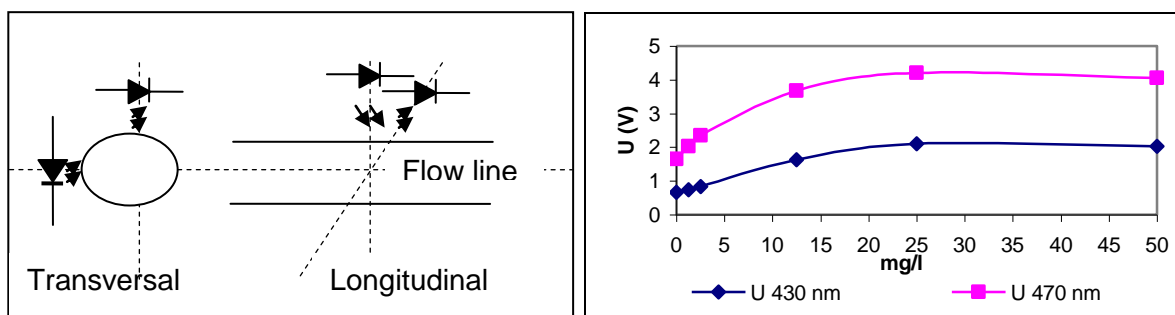

Fig. 3: a) two tested transmittance position b) two tested wavelength excitation response

Final design and test of sensor

On the basis of the results obtained from test of the first design, the final design was equipped with the 470 nm LED emitter, 3/8 inch pipe line diameter and receptor of transmittance positioned transversally at 90°. Figure 4 shows electrical details of the sensor and data acquisition system used to acquire the voltage output via Virtual instrument (VI) developed in Lab View 6.0 software. The VI was configured for 1 to 10 Hz data acquisition frequency, to display output voltage chart in the front panel and to save data in text file which can be treated by spread sheet.
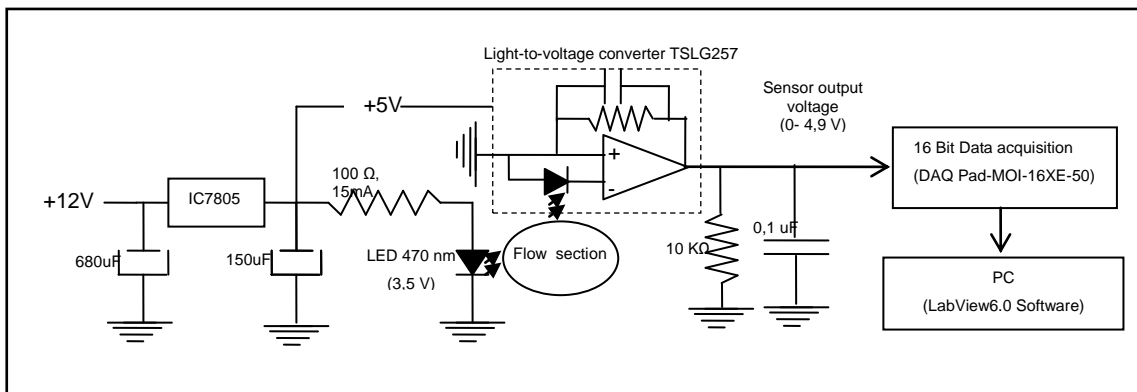

Fig 4: Electrical diagram of sensor and data acquisition system

Calibration of the sensor

To calibrate the sensor, 50 mg of powder fluorescein were weighted on a 0.1 mg precision scale (0.2%) and diluted in 5 liters of demineralised water added to buffer solution to stabilize pH at 7.2. The 10 mg/l mother solution was used to obtain diluted solutions of 4 liters for five different concentrations ranging from 0 to 2.5 mg/l by 0.5 mg/l step. Four laboratory glass recipients of 0.5% precision (2l±10 ml, 1l±5ml, 0.5l±2.5ml, 0.25l±1.25ml) were used to measure the volume of fluorescein mother solution needed and the volume of demineralised water to obtain the 4 liters of each concentration. Each 4 liter's concentration was put in the 5 liters tank and sensed on-line by the sensor mounted upstream of a small 12V DC centrifugal pump (Totton pumps, UK) in open flow rate loop of 0.75 l/min. The experimentation was carried out at 23 °C laboratory temperature and repeated four times independently. The voltage data of six concentrations (0, 0.5, 1, 1.5, 2 and 2.5 mg/l) was acquired for two minutes at 5 Hz, 30 min delay after the preparation of mother solution for each repetition. The mean and standard deviation of 500 values for each concentration and each repetition were calculated and are presented in table 1. The calibration curves are performed for two concentration range to show different linear regression responses and related correlations (fig 5).

Tab. 1: Calibration results of the sensor obtained with 4 repetitions

	Repetition 1		Repetition 2		Repetition 3		Repetition 4	
Concentration (mg/l)	Mean (V)	Standard deviation	Mean (V)	Standard deviation	Mean (V)	Standard deviation	Mean (V)	Standard deviation
0,0	0,301	0,001	0,290	0,001	0,292	0,001	0,292	0,001
0,5	1,164	0,002	1,129	0,001	1,130	0,002	1,180	0,001
1,0	1,922	0,002	1,967	0,001	1,973	0,001	1,983	0,001
1,5	2,676	0,002	2,707	0,001	2,702	0,002	2,674	0,001
2,0	3,345	0,001	3,323	0,001	3,327	0,001	3,327	0,003
2,5	3,900	0,001	-------	-------	3,895	0,002	3,891	0,001

The calibration results showed linear trends. The linearity increased under 1 mg/l comparatively to broader concentration range from 0 mg/l to 2.5 mg/l (fig.5). The sensor was therefore used to evaluate concentration variation around 0.5 mg/l set point in the 0 to 1 mg/l range, which presents the best performance because of the highest linearity (R^2= 0.9979).
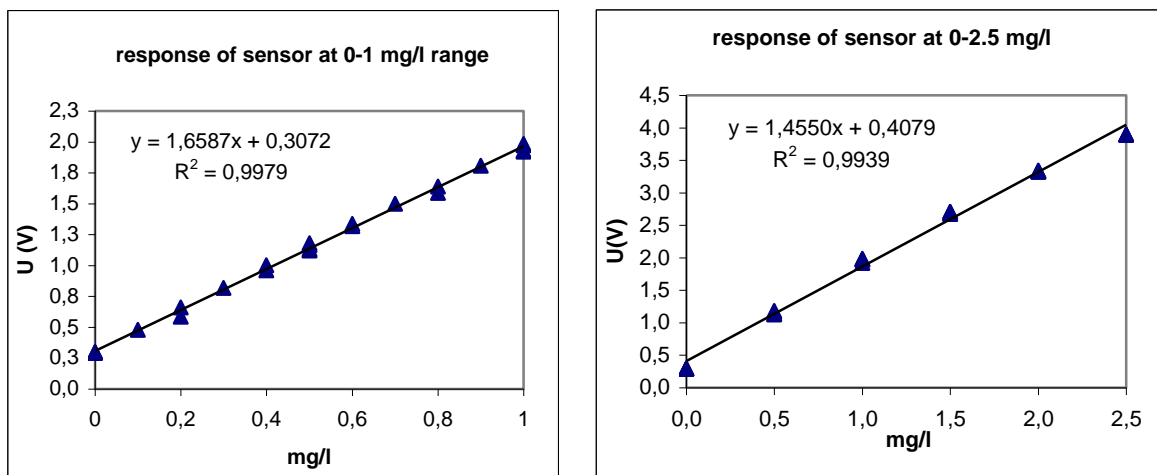

Fig. 5: Calibration curves of sensor at [0-1] and [0-2.5] concentration range (four repetitions)

The calibration equation [U(V)=1.6587C (mg/l)+0.3072] at [0-1mg] concentration ranges was used to evaluate relative error around 0.5 mg/l caused by the reference solution preparation (fig.5). The error can be written as follow:

$\Delta U/U = a\ \Delta C/C = a\ (\Delta M/M + \Delta V/V) = 1.6587\ (0.2\% + 0.5\%)$

$\Delta U/U = 1.16\%$

With: C: sensed concentration (C= M/V),

M: Mass of fluorescein active ingredient

V: volume of dilution

a: slope of linear regression equation (a= 1.6587)

This uncertainty (1.16 %) comes from experimentation conditions related to fluorescein weighting and dilutions preparation. It can cause distortion between repetitive measurements taken from different prepared concentrations regardless of proper sensor precision and stability of fluorescein by time. In fact, the fluorescein showed remarkable voltage response for concentration at µg/l level and the potential error of µg/l concentration order can occur at the sensed mg/l concentration level inducing voltage error.

Sensitivity test

This test was carried out to illustrate the smallest fluorescein concentration change that sensor can detected accurately. Figure 6 shows the sensor response for small concentration steps of fluorescein (from 0 to 0.2 mg/l). The trend is linear (R^2>99%) and slope (1.7 %) shows that 0.01 mg/l variation step can be sensed with 1.7 mV/µg. This result shows that sensor can measure sensitively the concentration at 0-1 mg/l range as it will be used for sensing 0.1 mg/l concentration scale
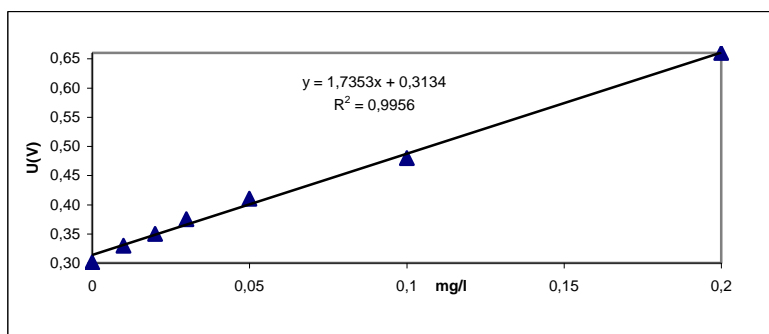

Fig. 6: response of sensor at [0 to 200 µg/l] range concentration

Photodegradation test

This test was conducted to show the influence of the external light on fluorescein transmittance fall. In fact, when fluorescein mixture is under external light and several repetitive excitation cycles, fluorescence intensity falls down due to photodegradation phenomena. The transmittance voltage was measured continuously with data acquisition system for one hour (1Hz).Two conditions, in the shade and under white LED lamplight (Luxueon III star, 12 V, 1400 mA). The final developed sensor was connected upstream to the small centrifugal pump in closed hydraulic loop of 1 l/min flow rate and 2 liter's recipient containing the mixture at 1 mg/l concentration. Fig 7 shows that transmittance voltage response of mixture in the shade decreased only, by 20 mV, for the first experiment (50 min). However, the transmittance decreased considerably (> 100 mV) under lamplight excitation in the second experiment (50 min). This remarkable voltage fall gave idea about the photodegradation induced by external light source that can occur along time. This problem

can be kept to acceptable levels by carrying out experimentation and calibrating sensor in dark conditions. The use of sensor in open loop hydraulic circuitry configuration gave constant transmittance voltage when the influence of external light on fluorescein mixture is attenuated or controlled for the stabilised conditions of sensor calibration and use.
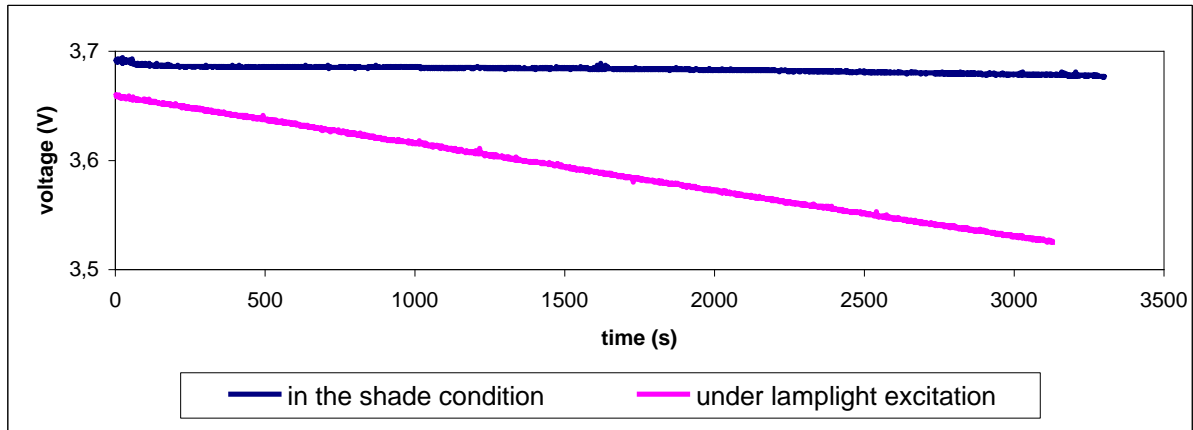

Fig. 7: Voltage transmittance decrease due to external light excitation of fluorescein

Conclusion

The developed on-line sensor can presents more accuracy and ease of use comparatively to static sampling methods using fluorometric tracers. It can be advantageously integrated online at different level of direct injection sprayers (upstream or downstream to pump or to boom). The few nanosecond response time of fluorescein ables the device to sense variation of concentration almost instantaneously. To evaluate dynamic performance of direct injection systems, the sensor can be used to measure accurately lag time needed to adjust application rate to a new set-up point. The use of the sensor for measuring concentration around 0.5 mg/l, give the possibility to monitor concentration variation accurately around the median value. The photodegradation phenomena of fluorescein can be avoided by calibrating sensor and carrying out laboratory and/or field test in the dark or in the shade environment condition. Otherwise, evaluation of the sensor performance to measure fluorescence in viscous and/or opaque mixture shows the limits use of sensor.

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