한국농업기계학회지 제21권 제2호. pp. 146~154. 1996

Flow Characteristics of Injected Concentrates in Spray Booms+

주입식 붐 방제기의 농약 혼합 유동특성+

Y.M.Koo, S.C.Young, D.K.Kuhlman
구영모*, 스티븐 영**, 데니스 쿨만**

적 요

농약의 직주입 혼합방식은 작업자의 안전에 기여하며 남은 농약은 용기와 함께 수거되어 재사용 되므로 환경보전 및 경제적 이점이 있다. 그러나 주입식 방제기의 분관내 농약혼합액이 노즐에 이르는 시간까지의 유동특성인 지연시간은 농약 살포량에 오차를 유발한다. 본 연구는 이 지연시간이 미치는 실제 살포오차의 정도를 파악하려 시뮬레이션을 행하였다.

시뮬레이션의 결과에 의하면 오차는 상당히 심각한 것으로 판단되었으며 지연시간을 단축하려는 여러 방법을 검토하였다. 분관의 직경을 줄여 유동속도를 빠르게 하거나, 혼입 농약의 양을 일정하게 유지하며 방제속도를 가능한 목표속도에 맞추는 방법 등은 약간의 오차를 줄일 수 있을 뿐이었고, 농약을 각 노즐에 주입함으로써 오차를 최소화할 수 있으나 미소계량의 문제를 내포하였다.

따라서 농도의 변화에 따른 지연시간을 없앤 직주입 총유량 제어방식을 통하여 노즐 배출유량을 방제속도의 변이에 따라 보상하며 비례적으로 농약을 주입하여 농도를 일정하게 유지할 수 있을 것으로 판단된다.

주요용어(Key Words) : 주입식 방제기(Direct Injection Sprayer), 방제작업자 안전(Applicator Safety), 시뮬레이션(Simulation), 재활용(Recycling), 살포오차(Application Error).

1. INTRODUCTION

Today, as always, it is important to design spray equipment that accurately controls the application rate. Misapplication can result in increased chemical expense, suppressed yields due to crop damage, competition of weeds or insects, and potential environmental hazards. However, a survey conducted indicated that only one out of four pesticide applications were applied within 5 percent of the intended rate(Rider and Dickey, 1982). This study, as well as others (Ozkan, 1986; Cupery, 1988), have prompted us to investigate methods of improving application accuracy. Improved accuracy is important not only because of economic concerns, but also because it may reduce hazards to humans and the environment.

A somewhat new method of controlling the application rate of a sprayer is to maintain a constant pressure at the nozzles and vary the chemical concentration by directly injecting chemi-

---

+ This paper was presented as ASAE paper 87－1602

* Dept of Agricultural Machinery, Kyungpook National University, Taegu, Korea.

** Dept. of Agricultural Engineering, Kansas State University, Manhattan, KS, USA.

cal concentrate into the spray boom. The biggest advantage of this "direct injection" method is that since mixing is performed "on-the-go", the operator does not come in contact with the chemical in its most concentrated form. Frost(1990) and Ghate and Perry(1994) constructed model sprayers that used the direct injection method and metering pumps to inject pesticide at a rate proportional to the forward speed of travel. Results indicated that uniformity of deposition for a miscible chemical was inferior to applications using conventional tank mixing methods and application errors resulted from changes in forward speed.

Groselle, et al.(1986) built an experimental sprayer to meter pesticides at rates proportional to forward speeds and inject it into individual nozzles near the spray nozzle tip. Adequate mixing of the chemical occurred even when injection took place in the nozzle body. Their results agree with the conclusions of a study on injection parameters by Miller and Smith(1992). Cho et al.(1985) conducted experiments on a spraying system which metered two chemicals simultaneously. They concluded that the concentration with respect to nozzle location and sampling time, while not completely uniform, was as good as tank mixing systems.

Since one of the specific objectives of the pesticide application research is to develop ground-based chemical application methods which allow precise control of application rate and minimize the hazards to operator and environment, direct injection seems worthy of investigation. However, direct injection is not without its problems. One problem which has been noted is that the time required for a change in concentration to reach the outermost nozzles on a typical boom may be significant. Therefore, the objective of this paper is to determine whether the delay times of a typical direct injection sprayer are significant in practical cases. This study analyzes the application errors of a typical direct injection sprayer by using a computer simulation which was verified through tests.

2. MATERIALS AND METHODS

A. Problem Statement

The amount of chemical formulation applied per hectare area can be expressed by

$$F=\frac{600\times Q\times C}{W\times S} \tag{1}$$

where F is the formulation application rate, the amount of chemical formulation applied per unit area(L/ha), Q is the nozzle flow rate of the spray mixture(L/min), C is the spray concentration, the ratio of the volume of formulation to the total volume of the spray mixture(unitless), W is spray width per nozzle(m), and S is travel speed (km/h).

If the application objective is a constant formulation application rate then the parameters Q, C, W, and S must be adjusted so that the formulation application rate remains constant. For a conventional tank mix sprayer the value of the concentration is set at the time the formulation is mixed in the tank. Likewise, the nozzle spacing is fixed, and not easily changed. This means the ratio of the nozzle flow rate to speed must be kept constant if F is to remain constant. Sprayer control systems are available which compensate for changes in the travel speed by adjusting the operating pressure at the spray boom which in turn affects the nozzle flow rate.

With a direct injection sprayer the nozzle flow rate remains constant and the ratio of the concentration to the speed is adjusted so that the formulation application rate remains constant (Eq. 1). This is possible since the mixing of the concentrate with the diluent occurs in the boom and the concentrate is metered at a rate proportional to forward speed. However, when a chemical is injected into a spray boom, a finite period of time is required for change in concentration to become fully established at the nozzles. Therefore, a transient error in pesticide application rate can result from a change in operating speed when even when metering is proportional to the speed. Tompkins et al.(1990) observed the delayed response time of injection sprayers.

Equation(1) assumes that there are no delays between the time when the chemical is injected into the boom and the time it takes to flow to each nozzle position. Thus, a potential problem which needs to be answered is: Is the delay between the time a chemical is injected into the boom and when it reaches the nozzles significant? This paper attempts to assess the physical significance of these time delays and project their impact on typical spraying situations.

B. Simulation Method

A simulation was written to model the operation of direct injection sprayers. The purpose of the simulation was to develop a tool to quickly evaluate various existing and new injection sprayer designs. The simulation can be used to estimate the application errors of direct injection sprayers which arise due to time delays of injected concentrates in the boom. The simulation will prove helpful in determining whether the delays are significant enough to discount the use of this method, whether modifications can be made in boom or spray controller design to improve operation, or whether an entirely different approach is warranted.

The program requires the following inputs: number of nozzles, nozzle spacing, nozzle flow rate, boom diameter, leader distance and the error criteria. The leader distance is the distance from the injection point to the innermost nozzle and the error criteria is a threshold value. Areas which have application errors which exceed the error criteria are tallied and reported at the end of the simulation. The application error is given by

$$E=\frac{F_a - F_d}{F^d}\times 100 \qquad (2)$$

where E is the application error(%), F_a and F_d are the actual and desired formulation application rates, respectively.

The simulation computes the average fluid velocity in each section of the boom and from this computes the time required for the injected chemical to reach each nozzle. The basic assumptions made here are that the chemical travels at the average velocity of the fluid in the boom, and that any movement by diffusion is negligible. DeTar(1983) presented a method for determining flush times for irrigation systems when the same flow rate is discharged from equally-spaced outlets along pipeline which has a constant cross-section. The simulation uses a similar method to determine the delay time at each nozzle.

Suppose that there are n nozzles on a boom, numbered 1 through n, with 1 being the outermost nozzle. If the flow rate of each nozzle is Q, the nozzle spacing is W, and the cross sectional area of the boom is A, then the average time required for a fluid particle to travel from nozzle position 2 to nozzle position 1 is $t_1=AW/Q$, and so on until in general $t_n=AW/nQ$. The total time, T_j, required to travel from the injection point to any nozzle j (j<n) is :

$$T_j = t_L + \sum_{i=j}^{n-1} t_j = t_L + \frac{AL}{Q}\left[\frac{1}{j} + \frac{1}{j+1} + \cdots + \frac{1}{n-1}\right] \tag{3}$$

where t_L is the time required to travel from the injection point to the nth (innermost) nozzle position through the leader. Using Eq.(3), the simulation computes the delay present at each nozzle. The concentration at nozzle j can then be determined by knowing what the metered concentration was Tj seconds in the past. By knowing what the actual concentration is and what the concentration should be(based on the current speed), the simulation keeps a running of tally of the application errors at each nozzle position. The area covered during the simulation depends on the simulation time, the speed of the sprayer and the width of the boom. The speed can be changed to simulate different operating maneuvers(eg. entering or exiting a field, crossing a terrace, etc.).

C. Experiment Method

In order to validate the results of the simulation, a spray boom was instrumented and dye tracers were used to measure actual time delays. A fluorescent dye(Rhodamine B), used in place of an actual pesticide, was injected into the boom through a metering orifice(Fig. 1). standard spray nozzles were installed at three of the four nozzle positions, spaced 50 cm apart. At the fourth position a fluorometer(Turner Co., model 100 with flow inlet), a device that measures fluorescence was installed. The flow through the fluorometer was throttled so that it matched the nozzle flow rate. Using the fluorometer it was possible to obtain an indication of the dye concentration at a nozzle location versus time. Two pressure transducers(Omega Eng'g Co., *PX236-100GV*), located before and after the metering orifice, were used to measure the boom and the injection pressures, respectively. The fluorometer and pressure transducers were interfaced to a microcomputer-based data acquisition system which read the fluorescence and pressure data.

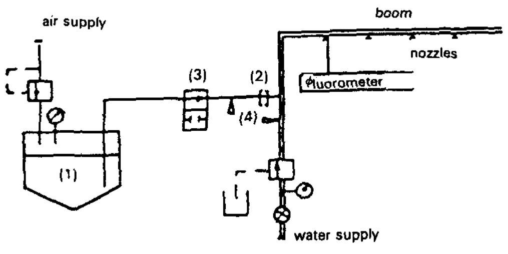


Fig. 1. Schematic of experimental setup to measure delay time for the direct injection method.

A factorial experimental design was used to analyze the time delays associated with the four nozzle positions. Three boom pressures, three injection pressures, and three nozzle sizes were tested and time delays recorded for each of the four nozzle positions. Three replications were made for each of the tests. Therefore, a total of 324 tests(3 nozzle size x 3 boom pressures x 3 injection pressures x 4 nozzle locations x 3 replications) were conducted. The injection orifice size remained constant for all tests. The boom pressures were 138, 207 and 276 kPa(20, 30 and 40 psi), and injection pressures were 69, 103 and 138 kPa(10, 15 and 20 psi) above the boom pressure. The nozzles used in the tests had flow rates of 6.3, 12.6 and 25.2ml/sec(8001, 8002 and 8004, Spraying Systems Co. ; 0.1, 0.2 and 0.4 gpm) at 276 kPa. The metering disc used for the injection orifice had a flow rate of 1.26 ml/sec(0.

02 gpm) at 138 kPa. Pipe diameters were 12.7 mm(1/2″), and 9.5 mm(3/8″) for the leader and the boom respectively.

The test procedure was to set the boom and injection pressures to the desired levels while no dye was being injected. The data acquisition system was then started and the dye control valve(quick shut off valve) was opened so that dye was injected into the boom. The acquisition system gathered data at the rate of 71 samples per second for 50 seconds, which was enough time for the dye concentration to reach equilibrium at all four nozzle positions. By examining the trace of the injection pressure transducer, it was possible to determine the instant at which the dye control valve was opened because a step increase(rise time<0.1 second) in pressure was observed. Using this as a reference point the time delay associated with dye reaching a nozzle was determined by examining the fluorometer data.

3. RESULTS AND DISCUSSION

A. Validation of Predicting Delay-time

Delay times were evaluated for step inputs using the fluorescent tracing technique. Figure 2 shows a typical plot of the delay times for the nozzles. The time to the first detectable change in concentration, called the theoretical delay time, for a given nozzle was found to be predictable using Eq.(3). The time between the instant that the change in concentration was first detected and when the new concentration became fully established at a nozzle was presumed to be a function of mixing and diffusion characteristics of the dye.

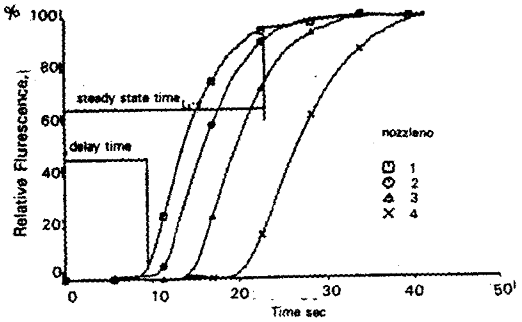


Fig. 2. A typical transient behaviors of dye concentration at the boom and injection pressures of 207 and 103 kPa, respectively.

Experimental results showed that there were sizeable time delays associated with spray equipment which injects chemicals directly into the spray boom. Theoretical delay times of up to 20 seconds were measured for the experimental setup. As was expected, changes in parameters which resulted in higher fluid velocities(i.e higher boom pressures or larger nozzle sizes) shortened the delay times(Figures 3(a) and 3 (b)). The effect of injection pressure was also found to be significant, however, it only slightly affected the delay time(Figure 3(c)).

Simulation results were compared to the experimental results. The comparisons are shown in Figures 4(a), (b) and (c) for nozzle flow rates of 6.3, 12.6, and 25.2 ml/sec, respectively. Differences may be due to the assumption made in the simulation that the dye moves through the boom as a continuous front. Also, differences may have been due to any specific plumbing characteristics of the instrumented boom or response characteristics of the fluorometer that were not accounted for in the simulation. The simulation results were close enough for use in predicting application errors which are important to evaluate direct injection sprayers and to model modified designs.

B. Estimation of Application Error

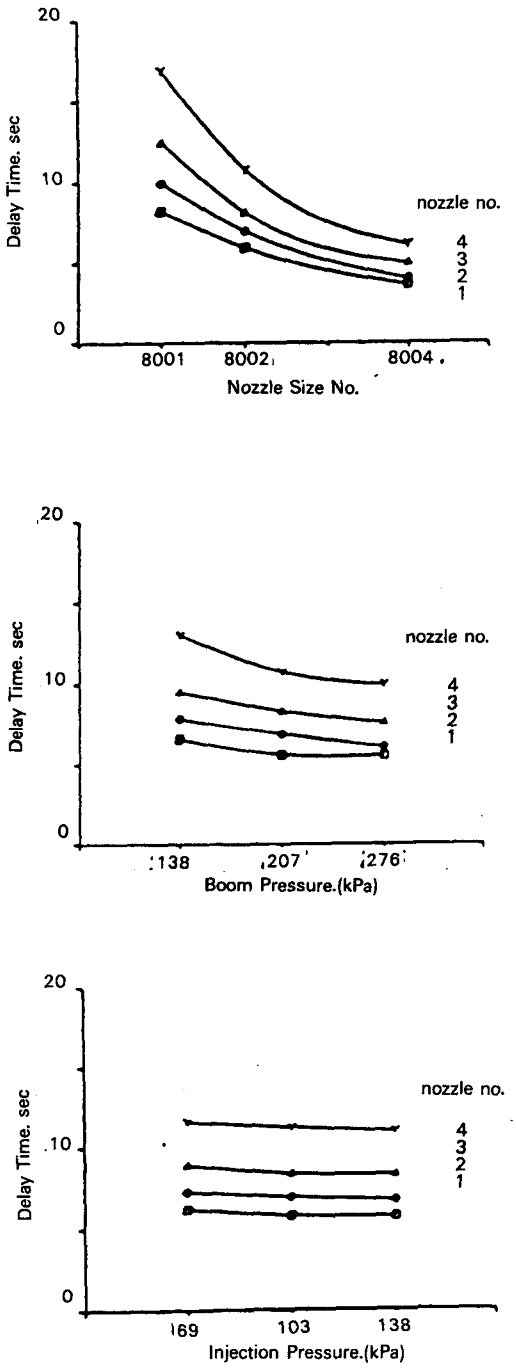


Fig. 3. Delay times at the four nozzle locations for the variables of(a) nozzle size(8001, 8002, 8004, Spraying System Co.), (b) boom pressure(138, 207, 276 kPa) and (c) injection pressure (69, 103, 138 kPa above boom pressure).

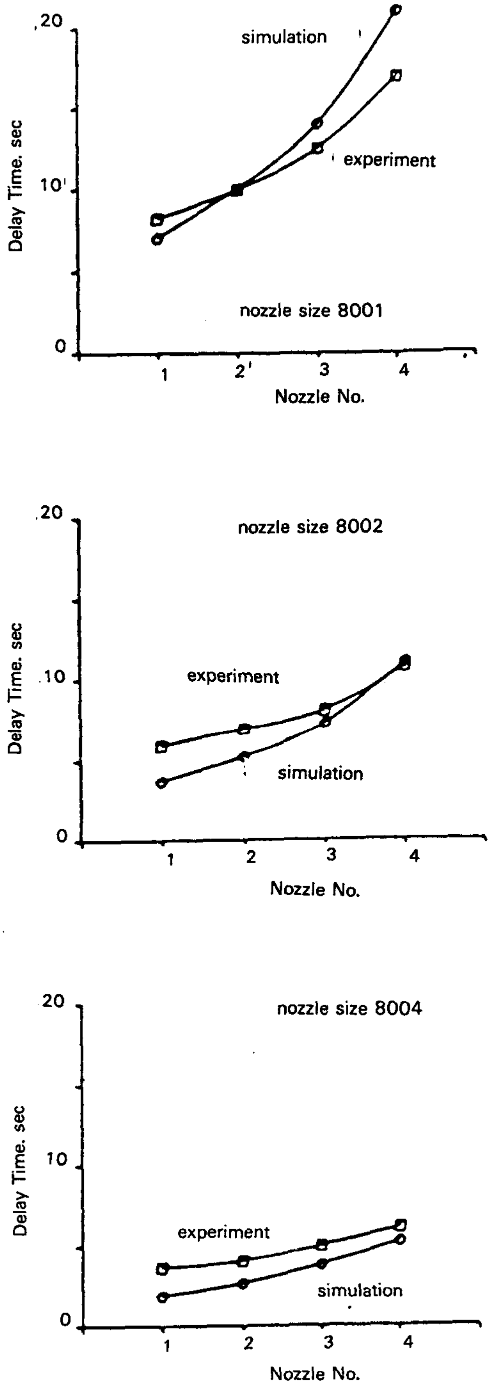


Fig. 4. Comparisons of experimental and simulated delay times at the four nozzle locations for the nozzle sizes of (a) 8001, (b) 8002 and (c) 8004 (Spraying System Co.).

In order to investigate application errors which occur due to the time delays that exist with direct injection sprayers three typical spraying maneuvers were simulated. The parameters for the sprayer used in the simulation are listed in Table 1. The error criteria used was 10%. That is, for each nozzle, the area covered in which absolute application errors exceed 10% is tallied.

Table 1. Sprayer parameters used in the simulation

Parameter	Value (unit)
Number of nozzles	12
Nozzle spacing	51cm
Nozzle flow rate	12.6 ml/sec
Boom diameter	19 mm
Leader length	152 cm
Error criteria	10 %

Three basic maneuvers were simulated as concentrate was metered into the boom at a rate proportional to the forward speed of travel. The first maneuver was a constant acceleration from 0 km/h to 9.6 km/h(6mph) in a period of 5 seconds. In this case the concentration in the boom takes 40 seconds before it reaches equilibrium. During the settling time the sprayer covered 612 m2 and 244 m2 or that area(40%) had an absolute application error of 10% or greater.

The second maneuver simulates the case in which the sprayer slows down to make a turn or negotiate an obstacle, such as a terrace. The sprayer decelerates from 9.6 km/h(6 mph) to 4.8 km/h(3mph) in a period of 5 seconds, continues at constant speed of 4.8 km/h for a period of 2.5 seconds, and accelerates back to 9.6 km/h in a period of 5 seconds. In this case the concentration in the boom takes 47 seconds before it reaches equilibrium. During this time the sprayer covered 714 m2 and 243 m2 of that area(34%) had an absolute application error of 10% or greater.

The third maneuver simulates the case in which the forward speed of the sprayer slightly varies about a desired forward speed of 9.6 km/h(6 mph). The speed of sprayer changes from 9.6 km/h to 11.0 km/h in 2.5 seconds, downs to 8.2 km/h in 5 seconds, and back to 9.6 km/h for 2.5 seconds. In this case the concentration in the boom takes 45 seconds before it reaches equilibrium. During the settling time the sprayer covered 734 m2 and 178 m2 of that area(24%) had an absolute application error of 10% or greater.

The fourth maneuver is a simulation for a hypothetical 16.2 ha(402m x 402m) field in which there are three terraces to be crossed and the sprayer must slow to turn around at the end of each pass. This simulation repetitively applies second case to simulate negotiating the terraces and turning around at the end of the field. In this case it took 1.5 hours to complete the spraying operation in this field. Forty-one per cent of the total field area or 6.7 ha had an absolute application error of 10% or greater.

4. CONCLUSIONS

The primary advantage of direct injection sprayers is that since the chemical concentrate is injected directly into the spray boom the operator does not have to perform the mixing operation and therefore is not exposed to the chemical in ist most concentrated form. A second advantage is that little or no waste occurs since only the amount needed is mixed since mixing occurs "on-the-go." However, it was found that the time required for an injected concentrate to travel from the injection point to a nozzle is not negligible for conventional sized booms. The delay times can lead to application errors over significant areas of the field being sprayed. Although it's difficult to assess the agronomic impact of application errors, we believe that the application errors are certainly large enough to indicate that steps should be taken to minimize the time delays. If the delays can be minimized so that errors are reduced to an acceptable level, the advantages of direct injection may outweigh the application errors which exist.

Anything which can be done to increase the flow velocity in the boom will in turn reduce delay times. For example reducing the boom diameter, or increasing the flow rate will decrease the delay time. For the fourth case, a reduction in boom diameter form 19 mm to 13 mm resulted in a reduction

in the area which had misapplication errors greater than 10% from 6.7 ha to 5.2 ha.

In some cases the fact that a direct injection sprayer meters concentrate into the boom at a rate proportional to the forward speed contributes to the error. It may be better to meter at a fixed rate and simply try to minimize the variations in speed which occur. For instance, for the fourth case, if the metering was set to give the proper application rate at 9.6 km/h, thirty percent of the total area would have application errors greater than 10%. This is a 25% reduction in the error rate from the case in which metering is at a rate proportional to the forward speed.

Intuitively, one might think that increasing the number of boom sections and injecting at each section would decrease the time delays, but this is not the case since this results in a corresponding reduction in flow velocity in each boom section. The only way it appears to eliminate the delays completely would be to inject the concentrates directly at each nozzle body using a low volume metering device. However, the complexity of injecting concentrate at each individual nozzle may not be warranted even if boom or spray controller design can minimize application errors.

For the future work, a direct-injection-mixing total-flow-control boom sprayer system is proposed according to the conclusion of this paper. In the system, chemicals are metered and injected proportionally to the diluent flow rate, so that the concentrations are kept constant while the main diluent flow is varied in response to changes in operating speed. The system can minimize operator exposure to chemicals and give a possibility of recycling containers with leftover that may cause environmental contamination.

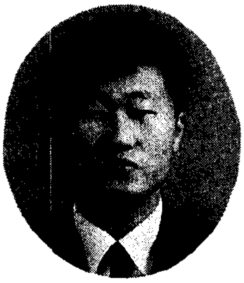
REFERENCES

1. Cho, H. K., S. J. Marley and J. L. Baker. 1985. Injection metering of spray concentrates. Paper No. MCR85-138. ASAE. St. Joseph, MI.
2. Cupery, W. E. 1988. Application accuracy. 63-83 in Methods of Applying Herbicides. Monograph No.4 of WSSA, C. G. McWhorter and M.R. Gebhardt, eds. Weed Scientist Society of America.
3. DeTar, W. R. 1983. Travel time for chemicals in an irrigation system. Transactions of the ASAE. 26(2) : 495-496
4. Frost, A. R. 1990. A pesticide metering system for use on agricultural spraying machines. Journal of Agricultural Engineering Research.(46) : 55-70.
5. Ghate, S. R. and C. D. Perry. 1994. Ground speed control of pesticide application rates in a compressed air direct injection sprayer. Transactions of the ASAE. 37(1) : 33-38.

6. Groselle, D. E., J. R. Stansell and J. R. Young. 1986. Effect of injection parameters on the droplet size of an oil formulated insecticide during chemigation. Transactions of the ASAE. 29(4) : 1065-1069
7. Miller, M. S. and D. B. Smith. 1992. A direct nozzle injection controlled rate spray boom. Transactions of the ASAE. 35(3) : 781-785.
8. Ozkan, H. E. 1986. Computer-assisted field evaluation of crop sprayers. Paper No. 86-1504. ASAE. Chicago, IL.
9. Rider, A. R. and E. C. Dickey. 1982. Field evaluation of calibration accuracy for pesticide application equipment. Transactions of the ASAE. 25(2) : 258-260.
10. Tompkins, F.D., K.D. Howard, C.R. Mote and R.S. Freeland. 1990. Boom flow characteristics with direct chemical injection. Transactions of the ASAE. 33(3) : 737-743.

축

학위취득



성명 : 이충호
생년월일 : 1967년 6월 7일
취득학위명 : 공학박사
학위수여대학 : 성균관대학교 대학원
학위취득년월일 : 1996년 2월 24일
학위논문 : 컴퓨터 시각에 의한 건표고의 외관검색 및 자동선별시스템 개발