

Theoretical performance simulation of a high pressure agro-forestry swirl nozzle

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Abstract: Equations of dynamic systems in droplet distribution at high pressure and boundary value flows in the swirl chamber of a swirl nozzle were used in conjunction with momentum equations of forces on moving curved vanes to develop mathematical models. A computer program in C++ language was developed and used to simulate the effect of some flow and geometric parameters, including flow rate, pressure and swirl chamber diameter, on the spray performance of a high pressure agro-forestry swirl nozzle. Each of the three performance parameters of axial flow rate, spray cone angle and output discharge (or performance) coefficient were studied as a function of any two combinations of the nozzle supply pressure, exit orifice diameter and swirl chamber diameter. The study established that the spray cone angle of the discharge flow pattern varied from the minimum value of 40° for a swirl chamber diameter of 90 mm to 220° for 40 mm as the exit orifice diameter varied from the minimum value of 0.5 mm to 4.0 mm. The simulated nozzle output discharge coefficient could be varied from 0.98, when the nozzle supply pressure was 400 kPa to the minimum value of 0.001 at any of the other six simulated nozzle supply pressure values of 200, 250, 300, 350, 450 and 500 kPa by varying the exit orifice diameter from 0.5 mm to 4.0 mm. The pattern of variation of the simulated nozzle discharge coefficient values were similar to those obtained by measurement during the validation exercise in the laboratory although their sensitivities to the independent variables were different. The results indicated that the range of nozzle discharge coefficient of 0.80 to 0.98 required for a well designed high pressure agro-forestry swirl nozzle has been simulated. With the successful development of the C++ computer program, a useful tool that will cut down on the rigor encountered and time spent by nozzle designers and evaluators during nozzle development process has been developed in the study.

Keywords: swirl-nozzle, simulation, agro-forestry, performance coefficient, spray cone angle, swirl chamber diameter

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1 Introduction

Agro-forestry is a farming system that integrates crops and/or livestock with trees and shrubs. It is an

effective way to conserve biodiversity because the resulting biological interactions between its components provide innumerable benefits which include diversified income sources, increased biological production, better water quality and improved habitat for both human and wildlife. The major constraint to production under agro-forestry farming system is inadequate and unsatisfactory control of pests and diseases. In Nigeria as well as most other developing African countries, crop spraying is still the best method of controlling pests in the agro-forestry system because uncontrolled bush burning kills non-target species that play a predominant role in the ecosystem under an Integrated Pest Control Method

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(IPM), which renders it ineffective. Unfortunately, crop spraying in agro-forestry systems in these countries has been abandoned and replaced by use of relatively ineffective and antiquated knapsack sprayers alone, thus leaving the fruits located on the top part of tall tree crowns at the mercies of the pests and pathogens because they are not within the reach of the spraying apparatus. Meanwhile, on-going efforts are currently being made by some researchers in this region to develop effective and affordable truck-mounted air blast assisted crop sprayers for use in the agro-forestry systems^[1,3,7].

Crop spraying is the application of certain organic and inorganic substances in solution form to field, garden and orchard crops with a view to combat their insect pests and associated plant diseases in addition to killing certain noxious weeds that may inhibit their achieving optimum production levels. The optimal method of pesticide application on the crops depends, to a large extent, on the product's mechanism of action (i.e. whether systemic or by contact) as well as on the nature of the target itself. In the case of foliage treatments, the droplets must be able to penetrate the crop canopy before it could achieve complete coverage of the target^[2]. When using products which act by contact, it is essential to cover the largest possible surface area, thus fine and medium fine droplets should be used with high impact. Due to their small sizes, the droplets are easily moved by high velocity air currents, thus improving their deposition on the under parts of the plants. Unfortunately, this ease of movement also implies that extra caution must be taken to avoid drift. The use of plant protection products with systemic mechanism, in its own case, does not require complete coverage of the target, but only that the plant under treatment must receive and absorb sufficient amount of the active ingredients^[2,11].

The effectiveness of any pest pathogen and weed control by spraying depends, to a great extent, on the performance of the spraying apparatus used for this purpose. With unsatisfactory operation and/or performance of the machine, harmful organisms and weeds may either remain unaffected or the principal crop may be damaged. High quality performance could only be achieved by adhering strictly to certain specific

agronomic and engineering requirements^[3,4,11]. The nozzle is a very important component of any spraying apparatus, if not the most important, simply because it performs three key functions of the sprayer, namely regulate flow, atomize the mixture into droplets, and disperse the spray in a specific pattern.

Bouse^[5] recognized the importance of nozzle and operation on atomization that increasing the spray pressure for solid stream nozzles oriented parallel to the air stream could reduce the relative velocity and increase the degree of atomization. Bouse^[5] further observed that the use of a flow restrictor with a tubular nozzle resulted in reduced liquid exit velocity and only small changes in relative velocity and atomization with increased pressure as flow rate increased four to six folds.

Koo and Kuhlman^[6] used the integral momentum method to analyze the boundary layer flow of a swirl-type nozzle. The fluid velocity profiles at the discharge orifice were derived, and essential structures of the spray performance models were identified from the theoretical analysis. The basic form of the discharge coefficient model was derived from the nozzle parameters to predict flow rate. They concluded that the derived theoretical spray performance would be verified and assessed for a specific design configuration of swirl nozzles. They also considered that the spray performance models could be used to predict the characteristics of swirl-type nozzles.

Prior to the development of a functional agro-forestry sprayer, general spray performance of swirl nozzles should be thoroughly investigated both in the laboratory and on the field. Therefore, the objectives of this study were to (1) obtain developed equations of dynamic systems in droplet distribution at high pressure and boundary value flows in the swirl chamber of a swirl nozzle from literature; (2) combine the equations with those of momentum forces on moving curved vanes and use to develop mathematical models of swirl nozzle spray performance; (3) use the models to write an interactive computer program in C++ language and use to simulate the theoretical performance of a swirl-type nozzle on a digital computer; (4) validate the simulated data of some of the key performance parameters with those obtained

from a developed experimental nozzle prototype subjected to laboratory tests in previous research efforts.

2 Materials and methods

In this study, the concept of a high pressure agro-forestry nozzle as developed in the report of Schwab et al.^[9] was used. The swirl nozzle is a pressure nozzle in which the stream of liquid flowing through it is set into a rotary motion by a swirl element which is in form of a cylindrical core insert with helical grooves cut on its surface. This is with a view to break up the stream just before or immediately after leaving the nozzle.

From the study of Bernacki et al.^[8], a swirl nozzle can be represented, for the purpose of mathematical model development and analysis, in the form of a container which has an orifice at the bottom. The liquid stream flows out of the orifice as a result of the difference in pressure between the container's interior and the outer space as shown in Figure 1. It was further explained that at a certain moment, the distance between the liquid element discharged and the chamber's axis will be equal to r if the outlet orifice radius is denoted by r_z . Furthermore, if the velocity of the liquid at the moment of its introduction into the chamber, that is, at the opening of the inlet of the chamber, amount to V_o , it will at a particular point in time amount to:

$$V = \frac{V_o R}{r} \tag{1}$$

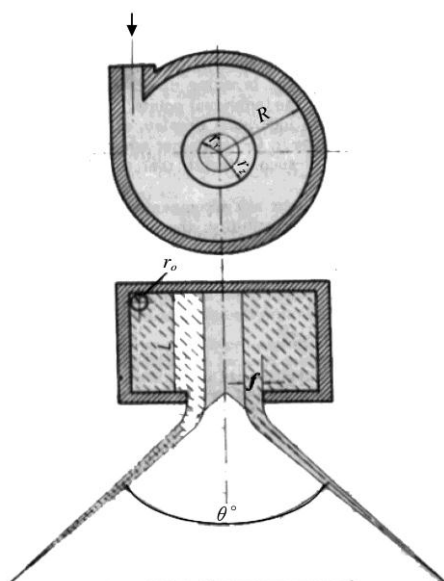


Figure 1 Schematic diagram illustrating liquid outflow from swirl nozzle^[8]

Equation (1) that holds true for an ideal liquid is assumed in accordance with the principle of conservation of momentums. Here, the negligible radial velocity component of the liquid has been left out. While, according to Bernoulli's equation, the situation at every particular point of the chamber is such that can be expressed by the formula below:

$$\frac{P}{\gamma} + \frac{V^2}{2g} + \frac{U^2}{2g} = H \tag{2}$$

where, P is static pressure at a particular point; V is tangential velocity of the liquid element; U is axial velocity of the liquid element; γ is specific weight of the liquid; H is total pressure in the nozzle chamber. Since H is constant, then if r tends to be zero, V tends to infinity in Equation (2), and therefore P should tend to negative value which, evidently, is out of the question. In consequence of the phenomena just explained, the static pressure P will, at a certain point in the chamber, fall below the atmospheric pressure value, and through the nozzle exit orifice, an "air core" of radius r_r will be formed inside (Figure 2). As a result of this, the liquid forms in the orifice a tube with a ring section with a thickness equal to:

$$f = r_z - r_r \tag{3}$$

Equations (1), (2) and (3) were used in the study of Koo and Kuhlman^[6] to derive the equations for solving the basic geometrical dimensions of the chamber. The pressure difference between the radius r_r and r_z amounts to:

$$P = \frac{1}{2} \frac{\gamma}{g} V_o R^2 \left(\frac{1}{r_r^2} - \frac{1}{r_z^2} \right) \tag{4}$$

where γ is the specific gravity of the liquid.

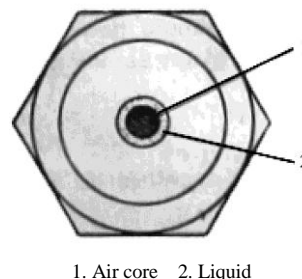


Figure 2 Air core in the orifice of a swirl nozzle^[8]

The tangential velocity, V_z in the outlet orifice was denoted by them as follows:

$$V_z^2 = V_o^2 \frac{R^2}{r_z^2} \quad (5)$$

whereas:

$$V_o = \frac{Q}{\pi r_o^2} \quad (6)$$

where, Q is the amount of liquid conveyed into the swirl chamber in a unit of time.

If the inlet opening is not round-shaped or if there are several such openings, then:

$$V_o = \frac{Q}{A_o} \quad (7)$$

where, A_o is the total surface area of the cross sections of all the inlet openings.

Hence:

$$V_z^2 = \frac{Q^2 R^2}{\pi r_o^2 r_z^2} \quad (8)$$

It was, however, noted by Schwab et al.^[9] that the whole liquid amount moves in the outlet orifice at the same exit axial velocity u_z along its entire length.

$$Q = \pi(r_z^2 - r_r^2)u_z \quad \text{or} \quad u_z = \frac{Q}{\pi(r_z^2 - r_r^2)} \quad (9)$$

Along this premise, mathematical models were developed from equations of boundary flows in the nozzle swirl chamber in conjunction with momentum equations of forces on moving curved vanes obtained from Ogboja^[10] and used to develop mathematical models of some key performance parameters of the swirl nozzle. These equations and the developed models which were later used to write interactive computer program in C++ language are shown as follows. The actual nozzle flow rate in litres per minute was converted to flow rate in cubic meters per second with:

$$Q1 = \frac{Q}{60000} \quad (10)$$

where, Q is flow rate in litres per minute; $Q1$ is flow rate in cubic meters per second.

The input exit orifice diameter in millimeters was converted into exit orifice diameter in meters as:

$$D_o = \frac{D_o(i)}{1000} \quad (11)$$

where $D_o(i)$ is input exit orifice diameter in millimeters.

The exit orifice area was computed as follows:

$$A_o = \frac{\pi D_o^2(i)}{4} \quad (12)$$

where, D_o is exit orifice diameter in meters.

The theoretical (or maximum) flow rate was computed as:

$$Q_{\max} = \sqrt{2000 \frac{P}{\rho} A_o^2} \quad (13)$$

where, P is nozzle supply pressure in kPa; ρ is Density of water in kilograms per cubic meter.

The nozzle discharge (or performance) coefficient was computed as follows:

$$C = \frac{Q}{Q_{\max}} \quad (14)$$

where, Q_{\max} is the theoretical (or maximum) flow rate, L/min.

The input swirl chamber diameter in millimeter was converted to swirl chamber diameter in meters as:

$$D_s = \frac{(D_s)i}{1000} \quad (15)$$

The bottom width (w), the projection (b) of the top edge of the trapezoidal sectioned helical grooves machined on the cylindrical surface of the swirl element (or core insert) on its base, and depth (y) were calculated on the basis of their individual relationships with the swirl chamber diameter as respectively explained by Schwab et al.^[9] as:

$$w = 0.111(D_s) \quad (16a)$$

$$b = 0.0833(D_s) \quad (16b)$$

$$y = 0.111(D_s) \quad (16c)$$

The equivalent radius of the trapezoidal-sectioned swirl chamber inlets was computed from the nozzle configuration reported by Taiwo and Oje^[1,7] as:

$$r_o = \sqrt{n \frac{y(w+b)}{\pi}} \quad (17)$$

where, n is the number of trapezoidal-sectioned helical grooves milled on the nozzle swirl element (or core insert).

The outflow coefficient, S , was defined by Taiwo and Oje^[1] as:

$$S = \frac{r_z}{r_o} \quad (18)$$

where, r_z is nozzle exit orifice diameter (mm); R is nozzle swirl chamber radius (mm). From which the corrected value of the outflow coefficient was computed as:

$$s^1 = S \left[\frac{r_z}{R - r_o} \right]^{1/2} \tag{19}$$

Equation (3) was used to establish a relationship just between f and r_z as:

$$f = 0.5r_z \tag{20}$$

Equation (21) was used to develop a model for the axial velocity of the working fluid discharged from the nozzle exit orifice as:

$$V_a = \frac{Q}{\pi \left(\frac{D}{2} \right)^2 - \left(\frac{D}{2} - 0.0222 \left(\frac{D}{2} \right) \right)^2} \frac{Q}{\pi \left(\frac{D}{2} \right)^2 - \left(\frac{D}{2} - 0.5 \left(\frac{D}{2} \right) \right)^2} \tag{21}$$

where, Q is amount of liquid conveyed into nozzle swirl chamber in a unit time (or flow rate) (m^3/sec); D is nozzle exit orifice diameter (m).

The nozzle spray cone angle, θ in degrees was computed by Bernacki et al.^[8] as:

$$\theta = 43.5 \log 14s^1 \tag{22}$$

The developed models were used to write an interactive computer program in C++ language whose flow chart is shown in Figure 3.

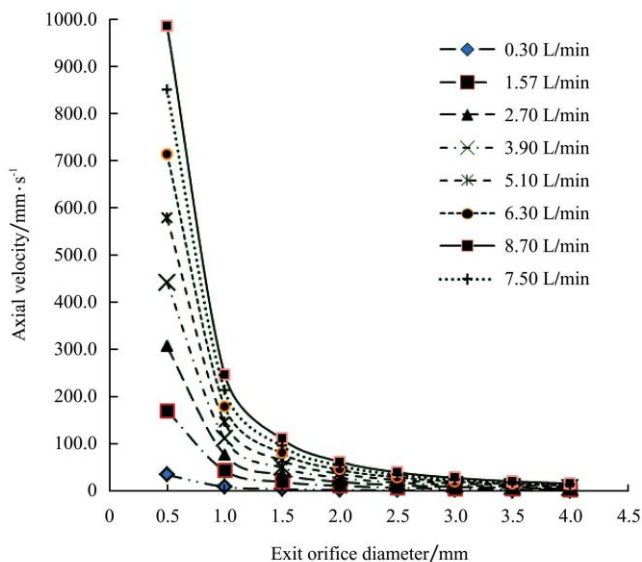


Figure 3 Effects of exit orifice diameter and actual flow rate on axial velocity

When the developed program was run on a digital computer, each output obtained for a particular input value of nozzle exit orifice diameter and other input parameters simulated in the program generated eight data points for each maximum (or theoretical) nozzle flow rate, tangential, axial and resultant velocities of the fluid

stream discharged from the nozzle exit orifice, exit orifice diameter, swirl chamber diameter, output discharge (or performance) coefficient and spray cone angle, making a total of 64 data points for each step of a particular input data simulated.

With Microsoft EXCEL package, these data points were carefully sorted out and used to generate tables which are consistent with the objectives of this study. These tables were later collated and plotted into graphs so the trends as well as the interrelationships between the parameters that significantly influence nozzle performance could be easily identified. The data obtained for output discharge (or performance) coefficient were later validated with those obtained from laboratory tests that were carried out in previous research efforts using the experimental swirl nozzle developed by Taiwo and Oje^[7].

3 Results and discussion

The programmed model simulation results for axial and tangential velocity of discharge, nozzle spray cone angle and discharge (or performance) coefficient are shown in Figures 3 to 6, respectively.

Figure 3 illustrates the effect of exit orifice size (0.5-4.0 mm diameter) on axial velocity component of the rotating liquid stream for simulated actual flow rates of 0.3, 1.5, 2.7, 3.9, 5.1, 6.3, 7.5, and 8.7 L/min, and liquid ring thickness 0.5 exit orifice diameter at 200 kPa nozzle supply pressure for a nozzle with 40 mm swirl chamber diameter. The axial velocity of the liquid ring was 246.1 mm/s and lower for all exit orifice sizes 1.0 mm diameter and larger at the estimated liquid ring size. The axial velocity components of the liquid ring at the exit orifice increased with increased nozzle discharge or flow rate, but decreased as initial exit orifice diameter increased. The range of axial velocities that can be tolerated depends on several factors including the range of estimated liquid thickness which, in turn, depends on the surface tension of the liquid^[3,6,8]. If the target is a tree crop planted in rows that is sprayed from a nozzle located at an angle of inclination to the horizontal axis and pointed to the tree crown, then a small amounts of droplets displacement by wind can result in large portions

of the spray missing the target, if it is not assisted by an auxiliary air blast. The smaller the exit orifice size, the worse is this scenario; this is perhaps, the reason why Klenin et al.^[11] recommended exit orifice diameter range of 1.5 mm to 4.0 mm for agro-forestry spray nozzles.

Figure 4 shows that when both actual flow rate and nozzle supply pressure were kept constant, the spray cone angle increased as exit orifice diameter increased and as the swirl chamber diameter decreased. This implies that liquid discharge from nozzles with small swirl chamber diameters will spread out more widely than those discharged from nozzles with large diameters. These results showed that for agro chemical application in agro-forestry systems, the chemical being distributed spread out over a large area, the nozzles with small swirl chamber diameter are preferred (Figure 4).

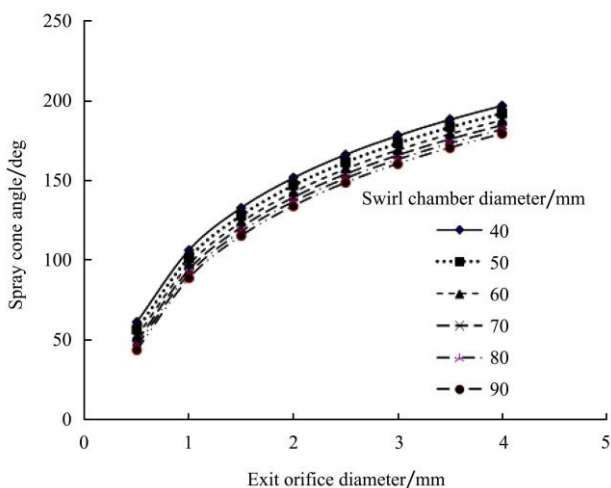


Figure 4 Effects of exit orifice diameter and actual flow rate on axial velocity

The intended type of application is on truck-mounted agro-forestry air blast assisted sprayer. In order words it is intended for only ground application. When the minimum simulated nozzle supply pressure of 200 kPa was increased steadily to the maximum simulated value of 500 kPa, the results shown in Figure 5 were obtained.

The results showed that nozzle supply pressure had effect on output discharge coefficient. The output discharge coefficient decreased as the nozzle supply pressure increased for any particular exit orifice diameter. It also decreased as the exit orifice diameter increased until it became asymptotic with the exit orifice axis at the maximum exit orifice diameter simulated. The rate had

the highest decrease between 0.5 mm and 1.0 mm exit orifice diameter for the three nozzle supply pressure levels simulated and intermediate for others. It was the highest for the lower pressure values for the nozzle exit orifice that ranged between 1.0 mm and 1.5 mm.

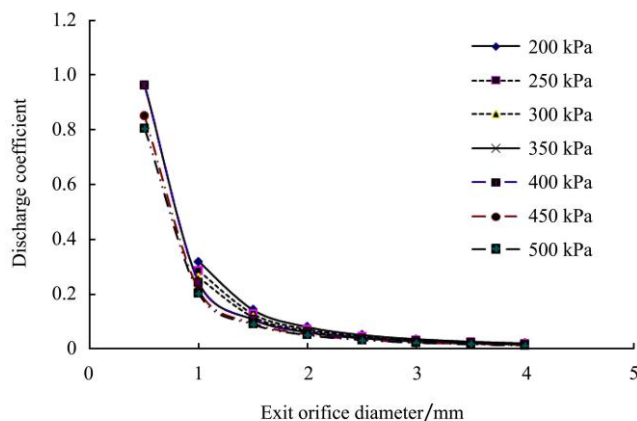


Figure 5 Effects of exit orifice diameter and nozzle supply pressure on discharge coefficient

It was also observed from Figure 5 that the nozzle output discharge (or performance) coefficient ranged between 0.8 and 0.98 for nozzle supply pressure values between 400 kPa and 500 kPa. The results shown in Figure 6 were obtained from the measured values of actual flow rate and exit orifice diameter variation effects on measured nozzle output discharge coefficient when both the swirl chamber diameter and nozzle supply pressure were kept constant during the validation exercise in the laboratory^[1,3]. When the minimum actual flow rate of 0.3 L/min increased steadily to the maximum value of 8.7 L/min, the results shown in Figure 6 were obtained. The results showed that actual nozzle flow rate had effect on output discharge coefficient; it increased as the actual flow rate increased throughout the range of the exit orifice diameter values measured, although it also decreased at a decreasing rate as the exit orifice diameter increased until it became asymptotic with the exit orifice axis at the maximum measured exit orifice diameter of 4.0 mm.

Although the effect of actual flow rate on discharge coefficient is somewhat similar to that of nozzle supply pressure, it is more significant. An observable difference between the two is the sensitivity of the output discharge coefficient to flow rate at all levels of simulated

nozzle exit orifice diameter. A unit change in actual flow rate produces larger change in output discharge coefficient than a unit change in nozzle supply pressure does at the same exit orifice diameter.

While in Figure 5 a change in nozzle supply pressure of 100 kPa produced a change in nozzle discharge coefficient of 0.09501 at 0.5 mm exit orifice diameter (equivalent to 0.0009501 per kPa); in Figure 6 a change in actual flow rate of only 7.2 L/min produced a change in nozzle discharge coefficient of 0.93 at 3.0 mm exit orifice diameter (equivalent to 0.129167 per L/min).

According to Schwab et al.^[9], the discharge (or performance) coefficient for a well designed nozzle ranges between 0.80 and 0.98. If this criterion is applied to Figure 6, since all the discharge coefficients of the prototype nozzle used in the validation exercise fall below the upper limits of 0.98, it implies that the nozzle was well designed. The similarity between Figures 5 and 6 confirms that the results obtained in Figure 6 validate those in Figure 5. This implies that the simulated models are correct mathematical descriptions of the swirl nozzle.

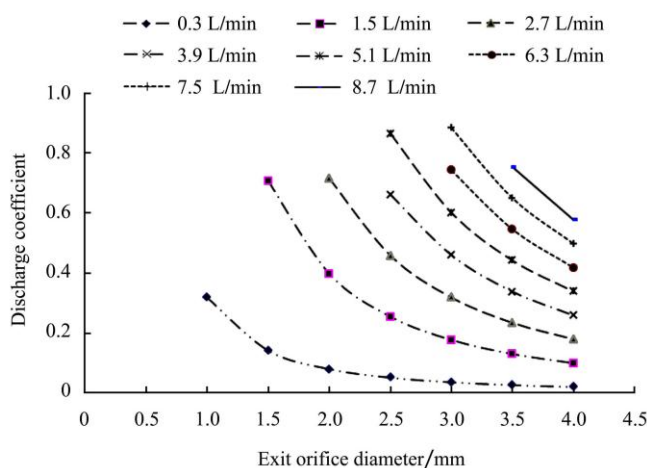


Figure 6 Effects of measured values of exit orifice diameter and actual flow rate on measured discharge coefficient

Applying this to Figures 5 and 6, it implies nozzles with swirl chamber diameter of 40 mm and exit orifice diameter of 0.75 mm fall into this category at the lowest extreme end whilst those with 90 mm swirl chamber diameter and 3.0 mm exit orifice diameter fall into it at the upper extreme end. In other words, it is the swirl nozzles with these geometrical configurations that could

be well designed.

The sensitivity of nozzle output (or performance) coefficient to variations in exit orifice diameter and flow rate is more pronounced in the measured values than in the simulated values even though they have similar pattern of variation. This observed interesting phenomenon may be due to differences in the thicknesses of their respective liquid stream rings formed at the exit orifice (Figures 1 and 2).

4 Conclusions

Developed mathematical spray performance models for swirl-type nozzles were obtained from literatures and used to write an interactive computer program in C++ language. The program was used to simulate the theoretical performance parameters of the nozzle consisting of the axial velocity of discharge at the exit orifice, spray cone angle and output discharge (or performance) coefficient. The simulated output discharge coefficient data were compared with those obtained from a prototype during a validation exercise in the laboratory in previous research efforts with a view to establish their accuracy. These data are very useful for the nozzle design engineers who will no longer need to use the conventional “trial-and-error method” in establishing key geometrical parameters such as swirl chamber diameter, optimum exit orifice diameter, etc., during the design process of their nozzles. The program can be used to predict the performance of nozzles even before they are fabricated. The implication of this in the real world is that there will be substantial reduction in the time consumed in the nozzle development process, as well as, substantial gain in their reliabilities when fully developed. The following specific conclusions could be drawn from the study:

- 1) Varying the exit orifice diameter from 0.5 mm to 4.0 mm in conjunction with flow rate from 0.3 L/min to 8.7 L/min enabled the variation of the axial velocity component of discharging ring-shaped liquid stream from 0.13 to 10.0 m/s at the exit orifice of a high pressure agro-forestry swirl nozzle when the thickness of the liquid ring is 50% of the exit orifice diameter.
- 2) Varying the exit orifice diameter from 0.5 mm to

4.0 mm simultaneously with swirl chamber diameter variation from 90 mm to 40 mm enabled the variation of the spray cone angle of liquid discharge from the nozzle to vary from 40 ° to 220 °.

3) The output discharge (or performance) coefficient of the nozzle varied from a maximum value of 0.98 when the nozzle supply pressure and exit orifice diameter were 400 kPa and 0.5 mm respectively to 0.001 when the exit orifice diameter was 4.0 mm for the seven simulated levels of nozzle supply pressure.

4) The out discharge coefficient decreased with increasing exit orifice diameter for each simulated value of the nozzle flow rate and increased with increasing flow rate at any of the eight simulated values of exit orifice diameter. The simulated models could not generate any value for exit orifice diameter of 0.5 mm at any of the seven simulated nozzle supply pressure levels.

5) The sensitivity of the nozzle discharge (or performance) coefficient to variation in exit orifice diameter and flow rate was higher than it was for variation in exit orifice diameter and nozzle supply pressure. While the discharge coefficient varied from 0.05 when the exit orifice diameter and flow rate were 2.5 mm and 0.3 L/min, respectively, to 0.98 when the flow rate was 5.1 L/min at the same exit orifice diameter, it remained at approximately 0.05 for all the seven simulated nozzle supply pressure levels at the same exit orifice diameter.

6) Although the pattern of variation of the simulated nozzle output discharge (or performance) coefficient was similar to those obtained by measurement from the developed nozzle prototype during the validation exercise in the laboratory, their sensitivities were different; the sensitivity of discharge coefficient to variations in exit

orifice diameter and flow rate was more pronounced in the measured values than in the simulated values.

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