5

Hydraulic nozzles

All sprayers have three features in common. Spray liquid is held in a container (spray tank) from which it is moved by pumps, pressure or a gravity-feed system to one or more outlets called nozzles. A nozzle is strictly the end of pipe through which liquid can emerge as a jet. In this book, the term 'nozzle' is used in the wider sense of any device through which spray liquid is emitted, broken up into droplets and dispersed at least over a short distance. Principally natural air movements influence further distribution of spray droplets, although on certain sprayers an airstream is used to direct droplets towards the appropriate target as described in Chapter 10.

In addition to hydraulic nozzles, sprayers may be fitted with other types using gaseous, centrifugal, kinetic, thermal and electrical energy (Table 5.1) to produce the spray droplets. A detailed description of atomisation and sprays is given by Lefebvre (1989), with special reference to the requirements in combustion technology. There is no universal nozzle, different designs being used to achieve the appropriate droplet spectrum. In this chapter the most common types of hydraulic nozzle are described, while alternative atomisers are included in Chapters 8–11. Major manufacturers of nozzles now have their own web sites that provide the latest information on the availability of different nozzles, which can also be purchased via the internet.

Most of the pesticide formulations described in Chapter 3 are diluted in water and applied through hydraulic nozzles. These nozzles meter the amount of liquid sprayed and form the pattern of the spray distribution in which the liquid breaks up into droplets. The droplet spectrum will depend on the output, spray angle of the nozzle and operating pressure, and this determines the spray quality. Correct choice of nozzle is therefore essential to ensure that expensive pesticides are applied effectively at the correct rate.

Table 5.1 Different types of nozzle and their main uses

Energy	Type	Uses
Hydraulic	Deflector	Coarse spray mainly for herbicide application
	Standard fan	Spraying flat surfaces, e.g. soil and walls[a]
	Pre-orifice fan	Fan pattern with reduced drift potential
	Air induction	Low drift potential, droplets contain air bubbles
	Boundary	Edge of boom to minimise deposit in buffer zone
	Offset	Lateral projection of spray, e.g. roadside
	Even-spray	Band sprays
	Cone	Foliar sprays, especially dicotyledon plants
	Solid stream	Spot treatment
Gaseous (see Chapters 10 and 11)	Twin fluid	Various, provide greater flexibility with control of both air and liquid flow
	Air shear	High velocity air stream to project droplets into trees and bushes
	Vortical	Aerosol (cold fog) space sprays
Centrifugal (see Chapter 8)	Spinning disc, Cage	Application of minimal volumes with controlled droplet size. Slow rotational speed: large droplets for placement sprays. Fast rotational speed: mist/aerosols for drift and space sprays
Thermal (see Chapter 11)	Fog	
Electrostatic (see Chapter 9)	Annular	ULV electrostatically charged spray

[a] Volume of spray depends on surface, i.e. runoff occurs at approximately 25 ml/m^2.

Types of hydraulic nozzle

Production of droplets

A large range of hydraulic nozzles have been designed in which liquid under pressure is forced through a small opening or orifice so that there is sufficient velocity energy to spread out the liquid, usually in a thin sheet which becomes unstable and disintegrates into droplets of different sizes. The pressure of liquid through the nozzle, surface tension, density and viscosity of the spray liquid and ambient air condition influence the development of the sheet. A minimum pressure is essential to provide sufficient velocity to overcome the contracting force of surface tension and to obtain full development of the spray pattern. For most nozzles the minimum pressure is at least 1 bar (14 p.s.i.), but higher pressures are often recommended when a finer spray is required, especially for fungicide and insecticide applications. An increase in pressure will increase the angle of the spray as it emerges through the orifice and also increase the flow rate in proportion to the square root of the pressure. Flow rate divided by the square root of the pressure differential is equal to a constant, commonly termed the flow number (FN).

Fraser (1958) noted three distinct modes of sheet – these are perforated, rim, and wavy-sheet disintegration (Fig. 5.1) – but only one mechanism of disintegration in which separate filaments of liquid break up into droplets. Perforated sheet disintegration occurs when holes develop in the sheet and, as

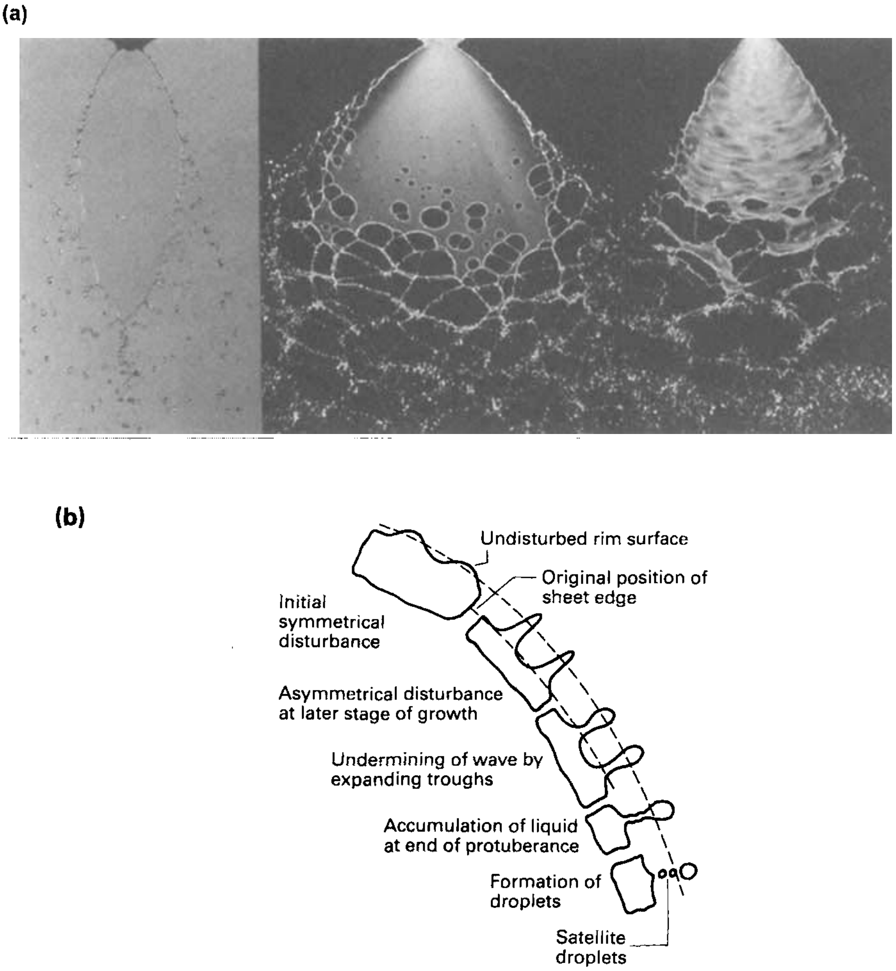


Fig. 5.1 (a) Rim, perforated sheet and wavy-sheet disintegration (photos: N. Dombrowski). (b) Diagram showing rim disintegration.

they expand, their boundaries form unstable filaments which eventually break into droplets. In rim disintegration, surface tension contracts the edge of the sheet to form rims from which large droplets are produced at low pressure, but at higher pressures threads of liquid are thrown from the edge of the sheet. Rim disintegration is similar to droplet formation from ligaments thrown from a centrifugal energy nozzle. Whereas in perforated sheet and rim disintegration, droplets are formed at the free edge of the sheet, wavy-sheet disintegration occurs when whole sections of the sheet are torn away before reaching the free edge (Clark and Dombrowski, 1972).

Recent studies using laser systems to measure droplet spectra combined with high-speed photography have examined the effects of emulsions on droplet production (Butler Ellis *et al.*, 1997a). They showed that emulsions resulted in perforated sheet formation, giving larger spray droplets than when spraying water alone. The influence of different adjuvants on the break-up is complex, with some such as Ethokem reducing the VMD compared to water, with break-up occurring further from the nozzle (Butler Ellis *et al.*, 1997b). When the sheet breaks up closer to the nozzle orifice, the VMD is generally larger, for example when the viscosity is increased by the addition of an oil plus emulsifier. Conversely, where the sheet remains stable and is stretched before breaking up into droplets, the thinner sheet forms a spray with a smaller VMD. The droplets vary considerably in size (Fig. 5.2) in the range 10–1000 μm, owing to the irregular break-up, so the volume of the largest droplets

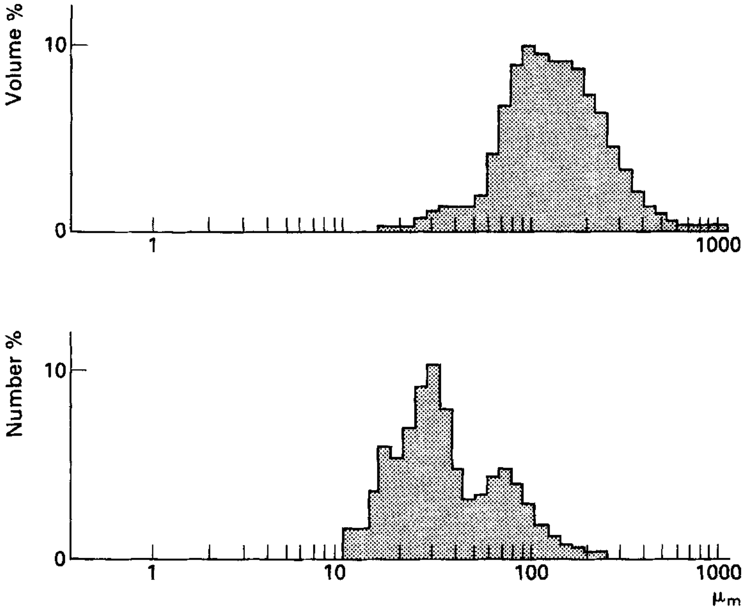


Fig. 5.2 Example of droplet distribution from a fan nozzle from Malvern particle size analyser.

is a million times that of the smallest. Their average size decreases with an increase in pressure and increases with a larger orifice. The range of sizes is less at the higher pressures, especially in excess of 15 bar. During forward movement of the sprayer, inwardly curling vortices are formed on either side of a flat-fan nozzle, so that small droplets are carried in a low energy trailing plume and are subsequently more vulnerable to drift away from the intended target (Young, 1991). Mokeba *et al.* (1998) have modelled the meteorological and spraying parameters that affect dispersion from the nozzle.

Particular interest has been directed at producing coarser sprays with fewer small droplets vulnerable to downwind movement by the wind. Thus in addition to standard types of hydraulic nozzles, several variations in design have been developed (see section below). With all the different types of hydraulic nozzle, the spray formation mechanism is similar, although changes in droplet size with some types makes it difficult to develop a model to predict the effects of adjuvants and spray drift potential (Butler Ellis and Tuck, 1999). An example of this is that the proportion of small droplets in a spray tends to increase with higher temperatures. However, when a polymer (e.g. Nalcotrol) was added to reduce drift the proportion of small droplets was not significantly influenced by temperature, although the VMD decreased with increasing temperature (Downer *et al.*, 1998b). Womac *et al.* (1997) published a set of droplet data for selected nozzles applying water, water + surfactant and a water–crop oil mix to assist users select nozzles for applying herbicides.

Components of hydraulic nozzle

Hydraulic nozzles consist of a body, cap, filter and tip. Various types of nozzle body are available with either male or female threads, or special clamps, sometimes with hose shanks, for connecting to booms (Fig. 5.3), and some nozzle tips are designed to screw directly into a boom without a special body or cap. On most large sprayers, the cap is attached to the body with a bayonet fitting. The body and cap of some nozzles have a hexagonal or milled surface or wings to facilitate tightening and eliminate leaks. The cap should be tightened by hand and where a seal is used, care should be taken to avoid damaging it. These components are more frequently moulded in plastic such as Kematal. Some nozzles are not provided with a filter, but as spray liquid is readily contaminated with dust or other foreign matter that can block the nozzle tip, a suitable filter should be used in the nozzle body, although on many sprayers a large capacity filter is in line with the boom. A 50-mesh filter is usually adequate, except for very small orifice tips when an 80-, 100- or 200-mesh filter may be needed. A coarse strainer, normally equivalent to 25-mesh, may be used with large orifice nozzles (Fig. 5.4). A filter fitted with a small spring and bolt valve as an antidrip device is not recommended because the spray operator is easily exposed to spray liquid when changing the nozzle tip. A diaphragm check valve is preferred as an antidrip device. It consists of a synthetic rubber diaphragm held by a low pressure spring held in place by a

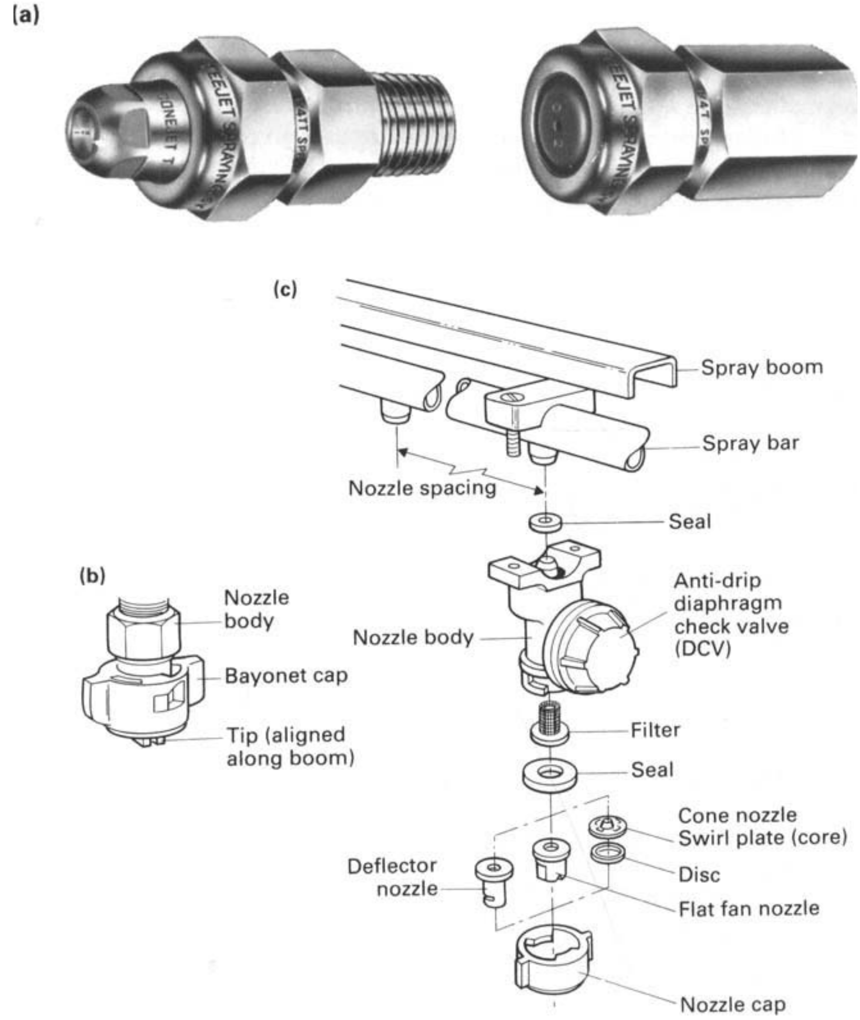


Fig. 5.3 (a) Hydraulic nozzles, male and female nozzle body (Spraying Systems Co.). (b) Plastic nozzle with bayonet cap and diaphragm check valve. (c) Exploded view of nozzle (Lurmark Ltd.).

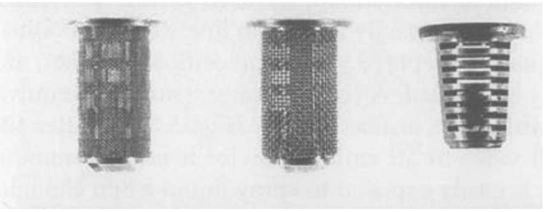


Fig. 5.4 Strainer, 50-mesh and 100-mesh filters (Spraying Systems Co.).

separate cap (Fig. 5.5). This valve can be replaced, especially on manually operated equipment by a ‘constant flow valve’ that in addition to being an antidrip device, ensures that liquid flows to the nozzle at a constant rate and/or pressure (see pp. 137–8).

Most nozzles are now manufactured from engineering plastics, rather than the traditional brass. The important aspect is that the components should not be affected by a wide range of chemicals. However, the orifice

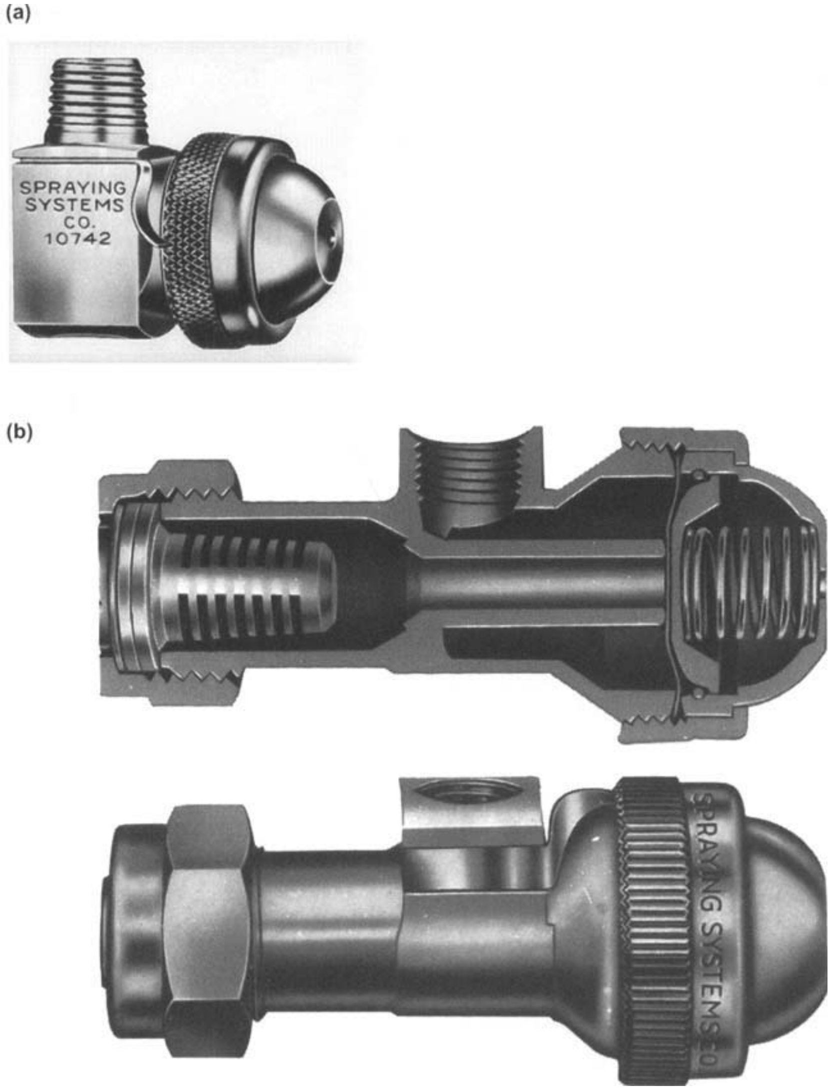


Fig. 5.5 (a) Diaphragm check valve. (b) Diaphragm check valve incorporated into nozzle body (Spraying Systems Co.).

can be easily abraded by particles, so many users prefer nozzle tips made in ceramics, although the plastic Kematal nozzles are inexpensive and easily replaced when worn. Plastic tips are sometimes more resistant to abrasion than metal tips because moulded tips have a smoother finish. The surface of metal tips has microscopic grooves as a result of machining and drilling the orifice; the rough finish presumably causes turbulence and enhances the abrasive action of particles suspended in a spray liquid. The threads of some nozzle bodies and caps manufactured in plastic are easily damaged by constant use, especially if they are over-tightened with a spanner. Various hydraulic nozzle tips are manufactured to provide differences in throughput, spray angle and pattern. The tip and cap of some nozzles are integrated. Ceramic and stainless steel tips are now often mounted in a plastic outer section.

Each manufacturer has its own system of identifying different nozzles, including colour coding, so an independent code has been introduced to be recommended without referring to an individual manufacturer. The code uses four parameters to describe a nozzle: the nozzle type, spray angle at a standard pressure, flow rate and the rated pressure (Table 5.2). As an example, F110/1.6/3 refers to 110 degree fan nozzle, 1.6 litres/min output at 3 bar. Information relating to standard fan nozzles is available for farmers in the UK on a chart (Fig 5.6) obtainable from the British Crop Protection Council. There is now a colour code (ISO 10625: 1996) which indicates the flow rate of fan type nozzles. Nozzles from the major manufacturers now conform to this standard (Table 5.3), but as different colour schemes were used, older nozzles need to be checked. The main advantage of a colour is that the user can readily see if all the nozzles on a spray boom have the same output. Choice of nozzle will also depend on the spray spectrum produced, so a system of spray categories is used to indicate the 'quality' of the droplet spectrum (Doble *et al.*, 1985) (Table 5.4).

Table 5.1 indicates a range of different types of hydraulic nozzle, details of which are given in the following section.

Table 5.2 Code for describing nozzles

Code	Nozzle type	Spray angle	Nozzle output	Rated pressure
F	Standard fan	Given in degrees (if known)	Given in litres per minute	Normally output is rated at 3 bar pressure, but some LP nozzles are rated at 1 bar
FE	Fan with even spray			
RD	Reduce drift, pre-orifice fan			
LP	Low pressure fan			
AI	Air inclusion			
D	Deflector			
HC	Hollow cone			
FC	Full cone			
OC	Offset fan			

Table 5.3 Colour code for fan nozzles based on nozzle output

BCPC nozzle code	Colour	Example of nozzle
F110/0.4/3	Orange	11001
F110/0.6/3	Green	110015
F110/0.8/3	Yellow	11002
F110/1.2/3	Blue	11003
F110/1.6/3	Red	11004
F110/2.0/3	Brown	11005
F110/2.4/3	Grey	11006
F110/3.2/3	White	11008

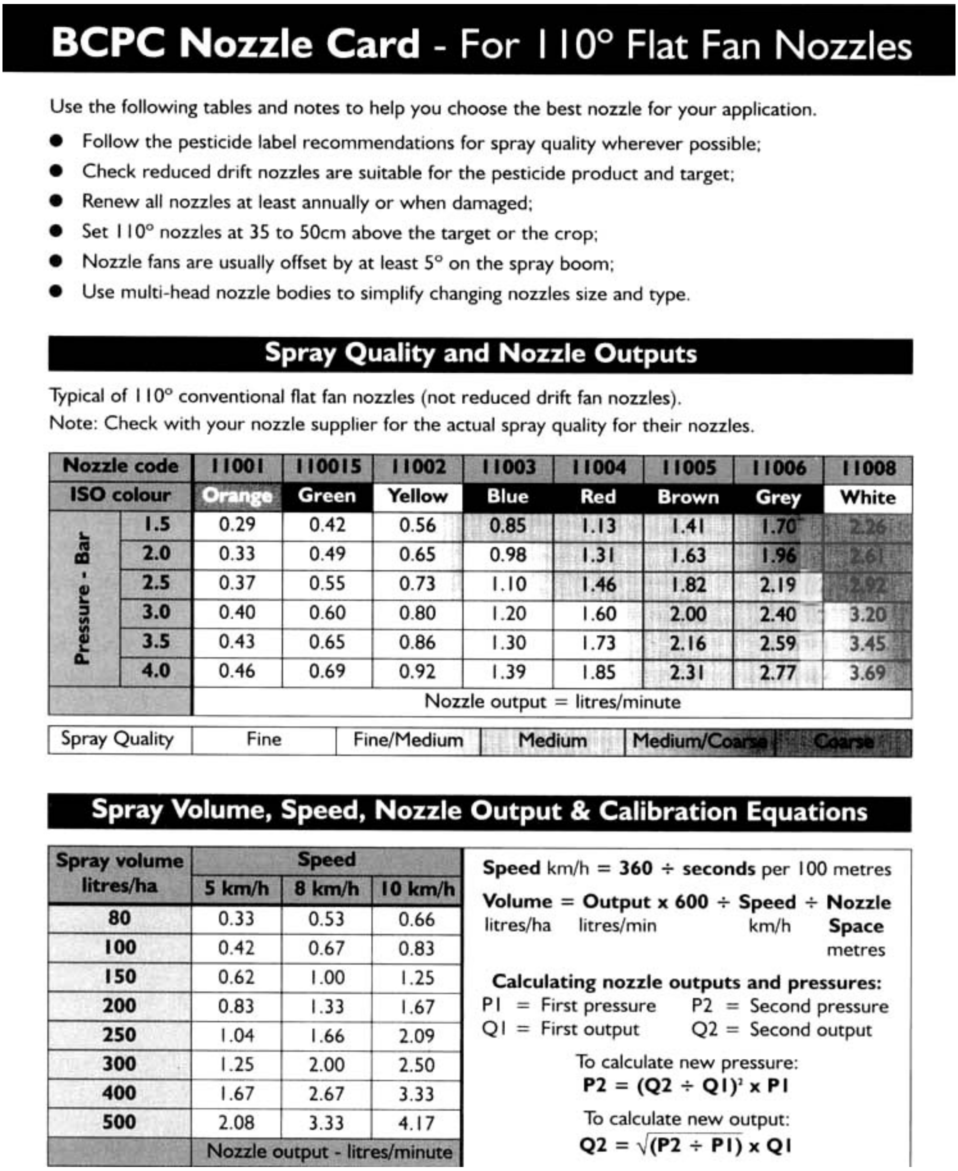
Nozzle tips

Deflector nozzle

A fan-shaped spray pattern is produced when a cylindrical jet of liquid passes through a relatively large orifice and impinges at high velocity on a smooth surface at a high angle of incidence (Fig. 5.7). Within most deflector nozzles, spray is projected at an angle away from the plane of the nozzle body. A relatively new design of deflector nozzle suitable for use on a tractor boom, ensures that they can be used instead of conventional fan nozzles without having to adjust the orientation of the boom (Figs 5.9, 5.10b). This is due to the internal design of the nozzle tip. The angle of the fan depends upon the angle of inclination of the surface to the jet of liquid. Droplets produced by this nozzle are large (>250 μm VMD) and there can be more spray at the edges of the fan (spray 'horns'). The deflector nozzle is normally operated at low pressures and has been widely used for herbicide application to reduce the number of small droplets liable to drift. When applying herbicides, the spray is normally directed downwards, but when used on a lance, the nozzle can be inverted to direct spray sideways under low branches. The effect of nozzle orientation on the spray pattern has been reported by Krishnan *et al.* (1989).

Deflector nozzles have been widely used where blockages could occur if a smaller elliptical fan nozzle orifice were used, and also where a wide swath is required with the minimum number of nozzles. They are sometimes referred to as flooding, anvil or impact nozzles. One type, known as the CP nozzle, is used on aircraft (see Chapter 13). This type of nozzle has been produced in plastic, colour-coded according to the size of orifice. A full circular pattern can be obtained if the side of the nozzle is not shrouded. Deflector nozzles have been used on fixed pipes in citrus orchards to apply nematicides, herbicides and systemic insecticides, metered into the irrigation water, around the base of individual trees. A deflector nozzle has also been used as part of a twin-fluid nozzle in which droplet formation and dispersal are affected by combinations of liquid and air pressure (see below).

(a)



BCPC Nozzle Card - For 110° Flat Fan Nozzles

Use the following tables and notes to help you choose the best nozzle for your application.

- Follow the pesticide label recommendations for spray quality wherever possible;
- Check reduced drift nozzles are suitable for the pesticide product and target;
- Renew all nozzles at least annually or when damaged;
- Set 110° nozzles at 35 to 50cm above the target or the crop;
- Nozzle fans are usually offset by at least 5° on the spray boom;
- Use multi-head nozzle bodies to simplify changing nozzles size and type.

Spray Quality and Nozzle Outputs

Typical of 110° conventional flat fan nozzles (not reduced drift fan nozzles).
Note: Check with your nozzle supplier for the actual spray quality for their nozzles.

Nozzle code		11001	110015	11002	11003	11004	11005	11006	11008
ISO colour		Orange	Green	Yellow	Blue	Red	Brown	Grey	White
Pressure - Bar	1.5	0.29	0.42	0.56	0.85	1.13	1.41	1.70	2.26
	2.0	0.33	0.49	0.65	0.98	1.31	1.63	1.96	2.61
	2.5	0.37	0.55	0.73	1.10	1.46	1.82	2.19	2.92
	3.0	0.40	0.60	0.80	1.20	1.60	2.00	2.40	3.20
	3.5	0.43	0.65	0.86	1.30	1.73	2.16	2.59	3.45
	4.0	0.46	0.69	0.92	1.39	1.85	2.31	2.77	3.69
		Nozzle output = litres/minute							

Spray Quality	Fine	Fine/Medium	Medium	Medium/Coarse	Coarse

Spray Volume, Speed, Nozzle Output & Calibration Equations

Spray volume litres/ha	Speed		
	5 km/h	8 km/h	10 km/h
80	0.33	0.53	0.66
100	0.42	0.67	0.83
150	0.62	1.00	1.25
200	0.83	1.33	1.67
250	1.04	1.66	2.09
300	1.25	2.00	2.50
400	1.67	2.67	3.33
500	2.08	3.33	4.17
	Nozzle output - litres/minute		

Speed km/h = **360 ÷ seconds** per 100 metres

Volume = **Output x 600 ÷ Speed ÷ Nozzle Space**
litres/ha litres/min km/h metres

Calculating nozzle outputs and pressures:
P1 = First pressure P2 = Second pressure
Q1 = First output Q2 = Second output

To calculate new pressure:

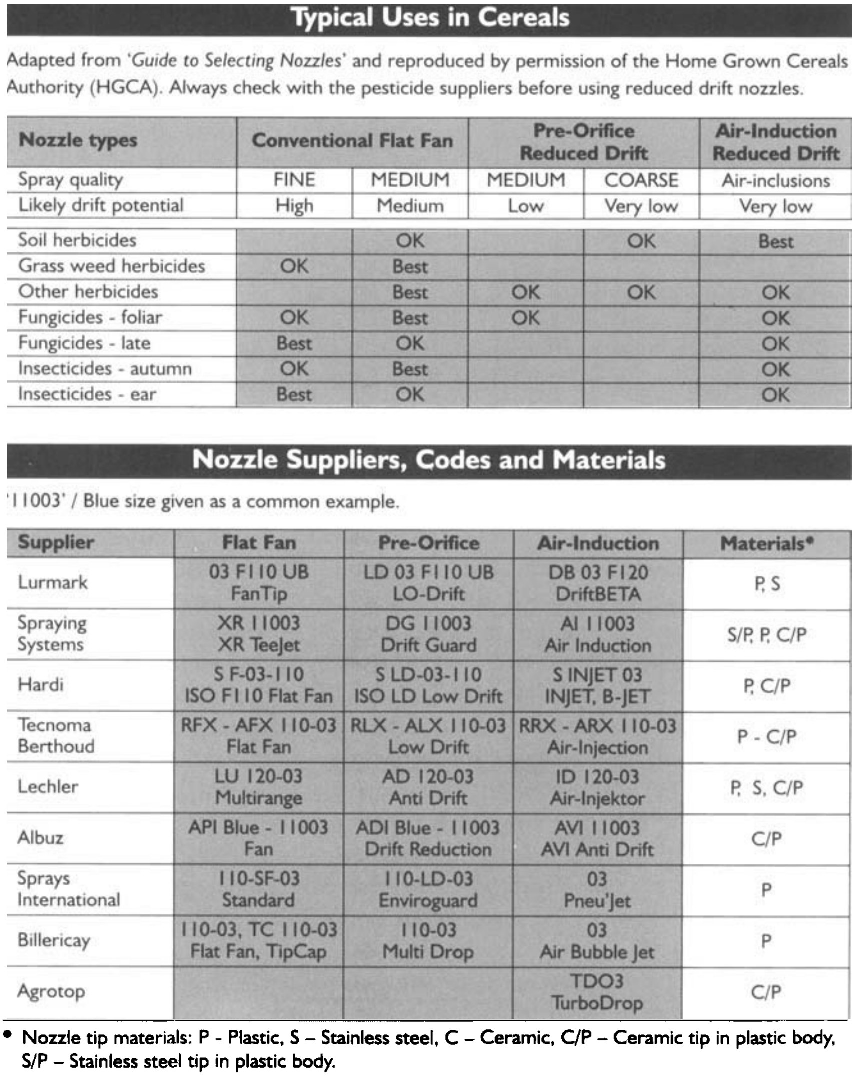
$$P2 = (Q2 \div Q1)^2 \times P1$$

To calculate new output:

$$Q2 = \sqrt{(P2 \div P1)} \times Q1$$

Fig. 5.6 British Crop Protection Council Guide Chart for flat fan nozzles with reference to spray quality, and suitability for different spraying operations.

(b)



Typical Uses in Cereals

Adapted from '*Guide to Selecting Nozzles*' and reproduced by permission of the Home Grown Cereals Authority (HGCA). Always check with the pesticide suppliers before using reduced drift nozzles.

Nozzle types	**Conventional Flat Fan**		**Pre-Orifice Reduced Drift**		**Air-Induction Reduced Drift**
Spray quality	FINE	MEDIUM	MEDIUM	COARSE	Air-inclusions
Likely drift potential	High	Medium	Low	Very low	Very low
Soil herbicides		OK		OK	Best
Grass weed herbicides	OK	Best			
Other herbicides		Best	OK	OK	OK
Fungicides - foliar	OK	Best	OK		OK
Fungicides - late	Best	OK			OK
Insecticides - autumn	OK	Best			OK
Insecticides - ear	Best	OK			OK

Nozzle Suppliers, Codes and Materials

'11003' / Blue size given as a common example.

Supplier	**Flat Fan**	**Pre-Orifice**	**Air-Induction**	**Materials***
Lurmark	03 F110 UB FanTip	LD 03 F110 UB LO-Drift	DB 03 F120 DriftBETA	P, S
Spraying Systems	XR 11003 XR TeeJet	DG 11003 Drift Guard	AI 11003 Air Induction	S/P, P, C/P
Hardi	S F-03-110 ISO F110 Flat Fan	S LD-03-110 ISO LD Low Drift	S INJET 03 INJET, B-JET	P, C/P
Tecnoma Berthoud	RFX - AFX 110-03 Flat Fan	RLX - ALX 110-03 Low Drift	RRX - ARX 110-03 Air-Injection	P - C/P
Lechler	LU 120-03 Multirange	AD 120-03 Anti Drift	ID 120-03 Air-Injektor	P, S, C/P
Albuz	API Blue - 11003 Fan	ADI Blue - 11003 Drift Reduction	AVI 11003 AVI Anti Drift	C/P
Sprays International	110-SF-03 Standard	110-LD-03 Enviroguard	03 Pneu'Jet	P
Billericay	110-03, TC 110-03 Flat Fan, TipCap	110-03 Multi Drop	03 Air Bubble Jet	P
Agrotop			TDO3 TurboDrop	C/P

- **Nozzle tip materials: P - Plastic, S – Stainless steel, C – Ceramic, C/P – Ceramic tip in plastic body, S/P – Stainless steel tip in plastic body.**

Standard fan nozzle

If two jets of liquid strike each other at an angle greater than 90°, a thin sheet is produced in a plane perpendicular to the plane of the jets. The internal shape of a fan nozzle is made to cause liquid from a single direction to curve inwards so that two streams of liquid meet at a lenticular or elliptical orifice. The shape of the orifice is very important in determining not only the amount of liquid emitted but also the shape of the sheet emerging through it, particularly the

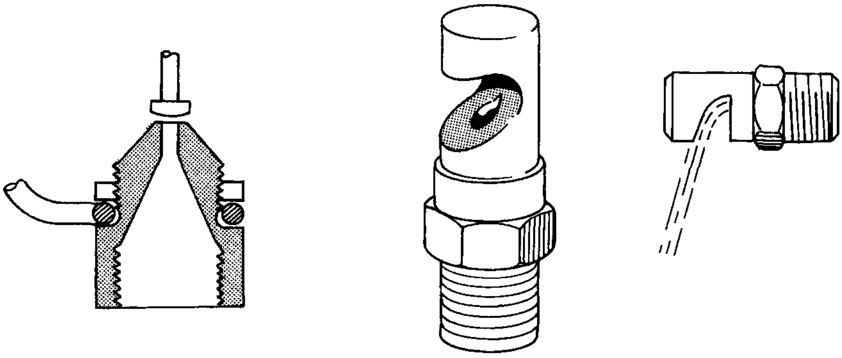


Fig. 5.7 Deflector nozzles (after WHO, 1974).

spray angle. The angle and throughput of fan nozzles used for applying pesticides are normally measured at a pressure of 3 bar. Snyder *et al.* (1989) give data for fan nozzles used in industrial applications and show the effect of viscosity, surface tension and nozzle size on the Sauter mean diameter over a wide range of pressures. An example of a range of fan nozzles is shown in Fig. 5.9.

Many farmers prefer to use 110° rather than 80° or 65° nozzles to reduce the number required on a boom or to lower the boom to reduce the effect of drift, although droplets are on average smaller with the wider angle. Boom height is very important and computer simulations have predicted more drift from 80° angle nozzles 50 cm above the crop compared to 110° nozzles at 35 cm height (Hobson *et al.*, 1990). Boom height can also be reduced by directing the spray forwards, instead of directly down into the crop. Some manufacturers produce a twin fan, so that one is directed forwards at an angle while the other fan is directed at a similar angle backwards. Other manufacturers provide a twin cap that will hold two fan nozzles. Angling the spray will improve coverage on the more vertical leaves.

The spray pattern usually has a tapered edge with the lenticular shape of orifice (Fig. 5.8), and these nozzles may be offset at 5° to the boom to separate overlapping spray patterns and avoid droplets coalescing between the nozzle and target. Great care must be taken to ensure that all the nozzles along a boom are the same and that they are spaced to provide the correct overlap according to the boom height and the crop which is being sprayed. Details of the position of nozzles and boom height on tractor sprayers are given in Chapter 7. Fan nozzles are ideal for spraying 'flat' surfaces such as the soil surface and walls. They have been widely used on conventional tractor and aerial spray booms and on compression sprayers for spraying huts to control mosquitoes (Gratz and Dawson, 1963).

Standard fan nozzles produce a relatively high proportion of droplets smaller than 100 μm diameter, especially at low flow rates and high pressures. Sarker *et al.* (1997), using a F110/0.8/3 nozzle at 300 kPa in a wind tunnel,

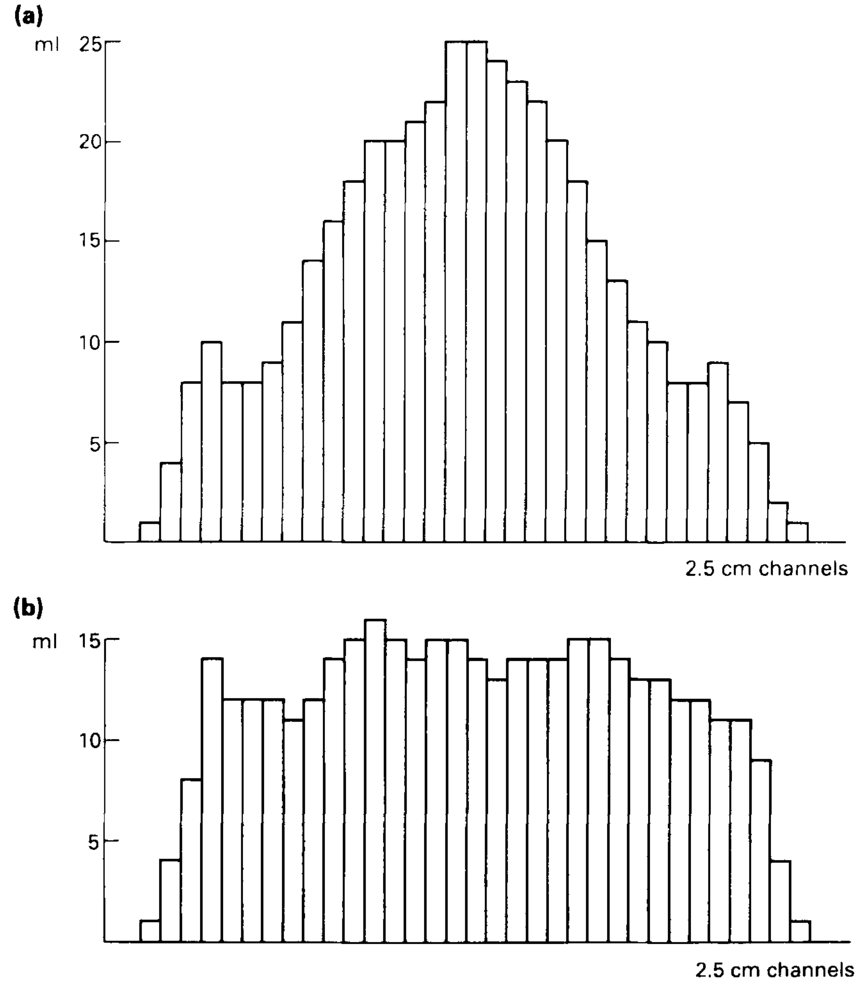


Fig. 5.8 (a) Spray pattern with a fan nozzles. (b) Spray pattern with an even-spray nozzle.

showed that drift potential increased as dynamic surface tension of the spray liquid decreased. Spray drift in these tests also increased marginally with an increase in viscosity.

A number of other fan nozzles are now available as alternative to a standard fan nozzle (Fig 5.9).

Low pressure fan nozzle

Low-pressure fan nozzles provide the same throughput and angle of a conventional fan tip, but at a pressure of 1 bar instead of 3 bar (Bouse *et al.*, 1976). Other low drift nozzles have to a large extent superseded these.

Table 5.4 Spray quality for agricultural nozzles

Spray quality	Retention on difficult leaf surfaces	Used for	Drift hazard
Very fine	Good	Exceptional circumstances	High
Fine	Good	Good coverage	Medium
Medium	Good	Most products	Low
Coarse	Variable	Soil applied herbicides, but with aerated droplets is also suitable for foliar application of systemic or translocated pesticides	
Very coarse	Poor	Liquid fertiliser	Very low

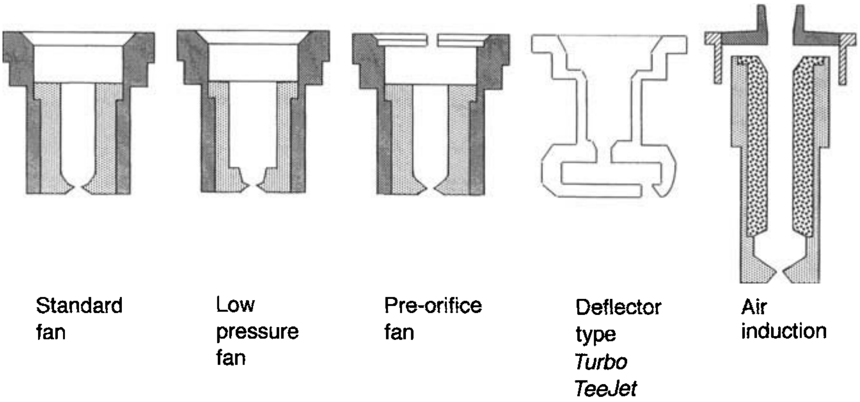


Fig. 5.9 Alternative designs of flat-fan nozzle, including one design of deflector nozzle.

Pre-orifice fan nozzles

Another modification of a fan nozzle is to incorporate a second orifice upstream of the tip. This is referred to as a 'pre-orifice' nozzle. The aim is to decrease the pressure through the nozzle and thus reduce the proportion of spray in droplets smaller than 100 µm (Barnett and Matthews, 1992).

Air induction nozzles

Another design based on the foam type nozzle, is the 'air-induction' nozzle which has an air inlet so that a venturi action of liquid through the nozzle sucks in air (Cecil, 1997; Piggott and Matthews, 1999). The nozzles produce larger droplets, many of which contain one or more bubbles of air. The presence of the air bubbles makes analysis of the droplet spectra more difficult with some laser equipment, when individual air bubbles are measured as droplets. Generally these nozzles produce a coarse spray (Fig. 5.10c) with less risk of spray-drift, but there is a wide variation in the spray quality produced with these nozzles due to the design of the venturi system (Piggott and Matthews, 1999). Etheridge *et al.* (1999) and Wolf *et al.* (1999) report similar droplet size data for herbicide sprays and compare an air induction nozzle with several other fan nozzles. The significant effect on spray droplet spectra from these nozzles by the addition of an adjuvant was demonstrated by Butler Ellis and Tuck (2000), who confirmed the variation between air induction nozzles of the same output from different manufacturers (Fig. 5.11).

When an extremely coarse spray is applied, the number of droplets deposited per unit area is reduced unless the spray volume is increased. It has been suggested that the presence of air bubbles in the large droplet reduces the risk of a droplet bouncing off a leaf surface. Deposition on horizontal targets was better with air induction nozzles and similar to standard fan nozzles on vertical surfaces in wind speeds up to 4 m/s (Cooper and Taylor, 1999). Biological results, especially with systemic pesticides have been very acceptable, but Jensen (1999) reported that efficacy of some herbicides can be significantly reduced with low volume air induction nozzles. Wolf (2000) reporting on trials with 19 different herbicides, showed that in some cases the low drift nozzle performed better than conventional nozzles, and suggested that the coarsest spray should be avoided with contact herbicides and when targeting grassy weeds. Deposits on oats were poor with low drift nozzles (Nordbo *et al.*, 1995). When used on an air-assisted orchard sprayer, Heinkel *et al.* (2000) obtained as good control of scab and powdery mildew with air induction nozzles as hollow cone nozzles with certain fungicides, presumably due to redistribution of the active ingredient from spray deposits.

Boundary nozzles

A variation of the air induction nozzle provides a half spray angle, so that when fitted as the end nozzle of a boom, spray is directed down at the edge of the crop and not beyond into the field margin (Taylor *et al.*, 1999).

Even-spray fan nozzle

A narrow band of spray requires a rectangular spray pattern when herbicides are applied to avoid under-dosing the edges of the band, so a fan nozzle with an 'even-spray' pattern is required (Fig. 5.8b), especially with pre-emergence herbicides.

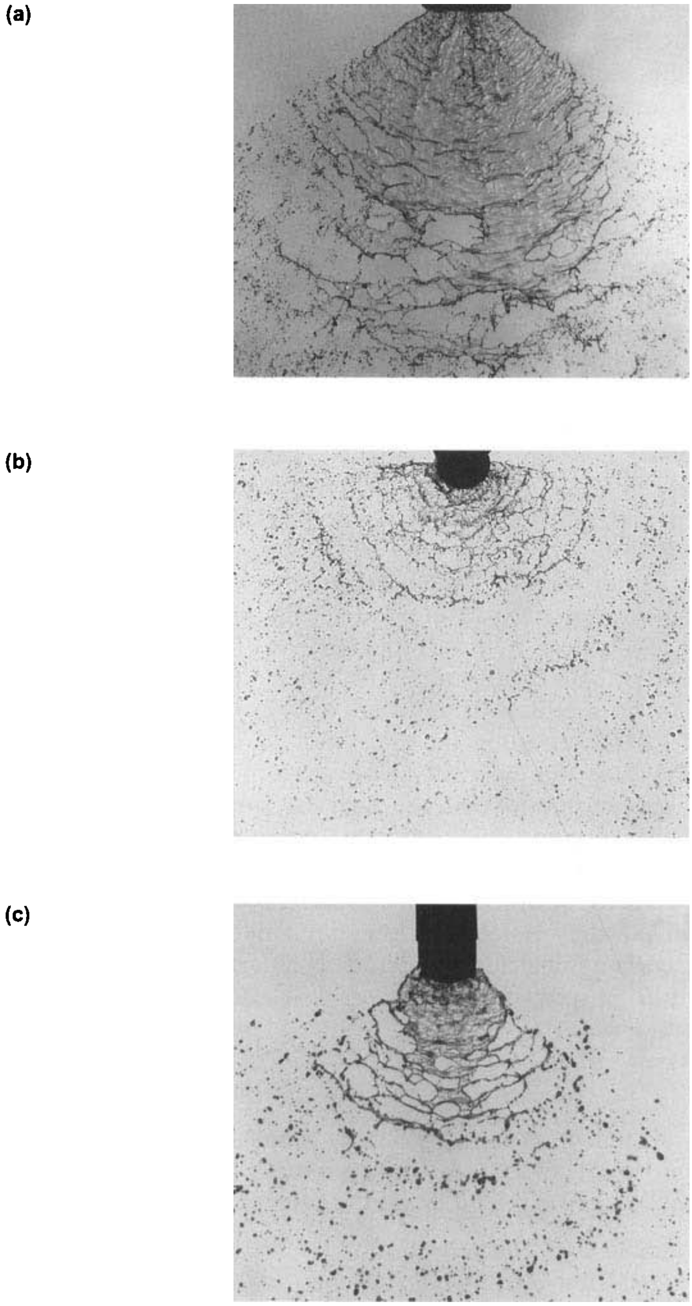


Fig. 5.10 (a) Standard fan nozzle spray pattern; (b) deflector nozzle (Turbo TeeJet); (c) air induction nozzle (Photos: SRI).

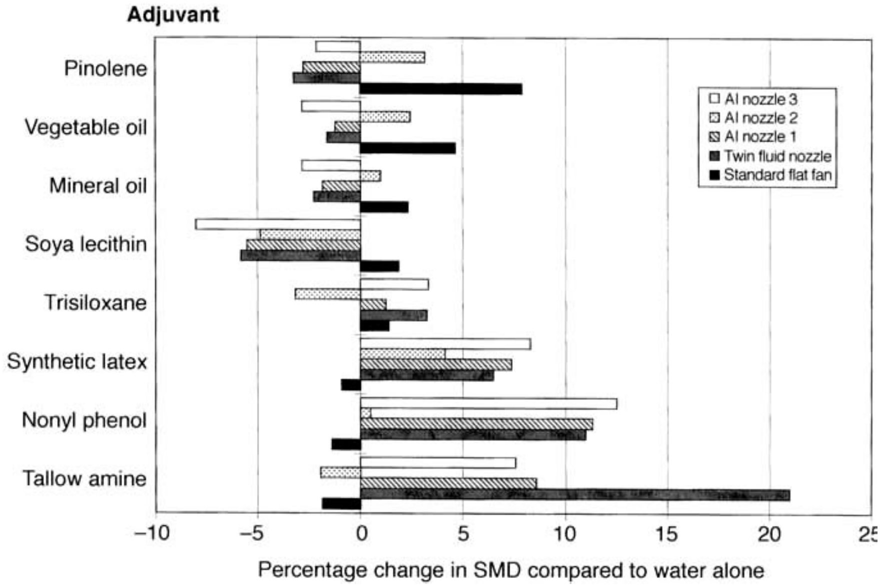


Fig. 5.11 Percentage change in Sauter mean diameter for eight adjuvants compared to water with five nozzles (SRI).

Cone nozzle

Liquid is forced through a swirl plate, having one or more tangential of helical slots or holes, into a swirl chamber (Fig. 5.12). An air core is formed as the liquid passes with a high rotational velocity from the swirl chamber through a circular orifice. The thin sheet of liquid emerging from the orifice forms a hollow cone (Fig. 5.13) as it moves away from the orifice, owing to the tangential and axial components of velocity. A solid cone pattern can be achieved by passing liquid centrally through the nozzle to fill the air core; this gives a narrower angle of spray and larger droplets. Some authors (e.g. Yates and Akesson, 1973) referred to the cone nozzles as centrifugal nozzles because the liquid is swirled through the orifice, but droplets are formed from the sheet of liquid in the same manner as with other hydraulic nozzles, so the term 'centrifugal' should be reserved for those nozzles with a rotating surface (spinning disc).

A wide range of throughputs, spray angles and droplet sizes can be obtained with various combinations of orifice size, number of slots or holes in the swirl plate, depth of the swirl chamber and the pressure of liquid. Some manufacturers designate orifice sizes in sixty-fourths of an inch; thus D2 and D3 discs have orifice diameters of 2/64 in (0.8 mm) and 3/64 in (1.2 mm), respectively.

Reducing the orifice diameter, with the same swirl plate and pressure, diminishes the spray angle and throughput (Table 5.5). The smaller the

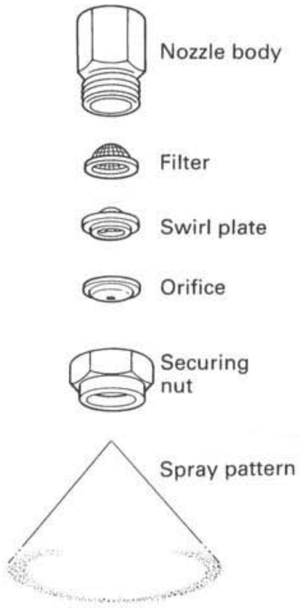


Fig. 5.12 Diagram of cone nozzle.

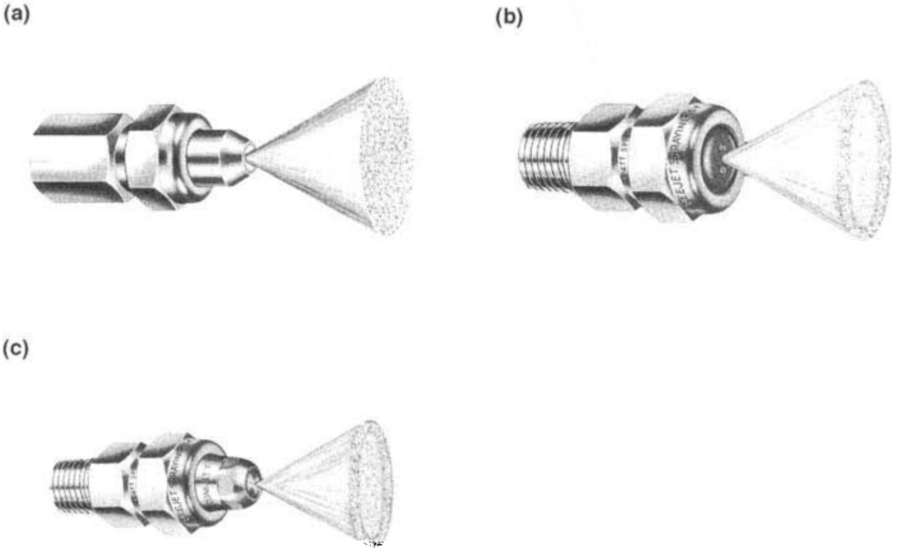


Fig. 5.13 (a) Solid cone. (b) Hollow-cone nozzle – disc type. (c) Hollow cone nozzle – 'Cone-Jet' type (Spraying Systems Co.).

Table 5.5 Effect on throughput and spray angle of certain combinations of disc and swirl plate of hollow–cone nozzles

Orifice	Orifice diameter (mm)	Swirl plate	Pressure (bar) 1.03		Pressure (bar) 2.8	
			Throughput (litres/min)	Angle (°)	Throughput (litres/min)	Angle (°)
D2	1.04	13	0.22	41	0.30	67
		25	0.38	32	0.61	51
		45	0.49	26	0.76	46
D4	1.60	13	0.31	64	0.45	79
		25	0.68	63	1.10	74
		45	0.83	59	1.36	69
D6	2.39	25	1.06	77	1.67	85
		45	1.32	70	2.20	79

openings are on the swirl plate, the greater the spin given to the spray. Also a wider cone and finer spray are produced with a smaller swirl opening. An increase in pressure for a given combination of nozzle and swirl plate increases the spray angle and throughput. On most cone nozzles, the orifice disc and swirl plates are separate parts. The depth of the swirl chamber between swirl plate and orifice disc can be increased with a washer to decrease the angle of the cone and increase droplet size. Where cone nozzles with a low flow rate are used, the swirl slots are cut on the back of the disc, and closed by a standard insert. On some nozzles, the flow rate can be adjusted if some of the liquid in the swirl chamber is allowed to return to the spray tank. Bode *et al.* (1979) and Ahmad *et al.* (1980, 1981) have investigated the use of these by-pass nozzles.

Variable-cone nozzles are available in which the depth of the swirl chamber can be adjusted during spraying, but this type of nozzle is suitable only when a straight jet or wide cone is needed at fairly short intervals, as intermediate positions cannot be easily duplicated. However, these nozzles are no longer generally recommended as the user is exposed to pesticide when adjusting the angle of spray, unless a special spray gun is used where a trigger mechanism adjusts the nozzles.

Cone nozzles have been used widely for spraying foliage because droplets approach leaves from more directions than in a single plane produced by a flat fan, although the latter can penetrate further between leaves of some crop canopies.

When a second chamber is positioned immediately after the orifice (Fig. 5.14), the proportion of small droplets is decreased. Air is drawn into this second chamber and mixes with swirling liquid, the net result of which is the production of larger, aerated droplets. This additional chamber on a nozzle operated at 2.8 bar can reduce the proportion of droplets of less than 100 μm diameter from over 15% to less than 1% (Brandenburg, 1974; Ware *et al.*, 1975). This type of nozzle is used for application of herbicides. An air induction cone nozzle is also available.

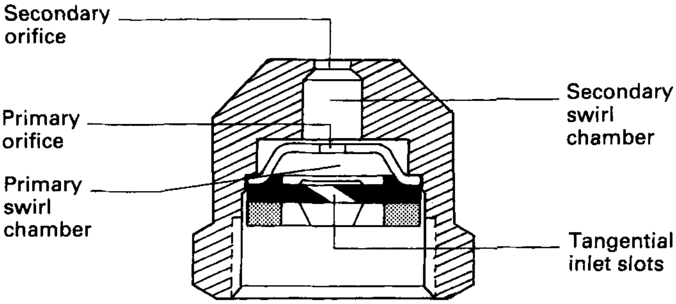


Fig. 5.14 Diagram of 'Raindrop' nozzle.

Plain jet or solid stream nozzle

This nozzle is similar to a cone nozzle but without a swirl chamber, and sometimes may have more than one orifice. It is used for various purposes including the spot treatment of weeds, young shrubs or trees with herbicide, and has been used to project spray to pods high in the canopy of cacao trees. This type of nozzle is used to apply molluscicides to control vectors of schistosomiasis to ponds and at intervals along canals where there is insufficient flow of water to redistribute chemical from a point source at the head of the canal. A long thin plastic tube attached to a solid stream nozzle has been used to inject pesticides into cracks and crevices for cockroach control.

Foam or air-aspirating nozzle

These nozzles were used primarily with additional surfactant to produce blobs of foam to indicate the end of the spray boom (Fig. 5.15). The use of 'tramlines' (p. 174) has reduced this need. Studies on the application of herbicide

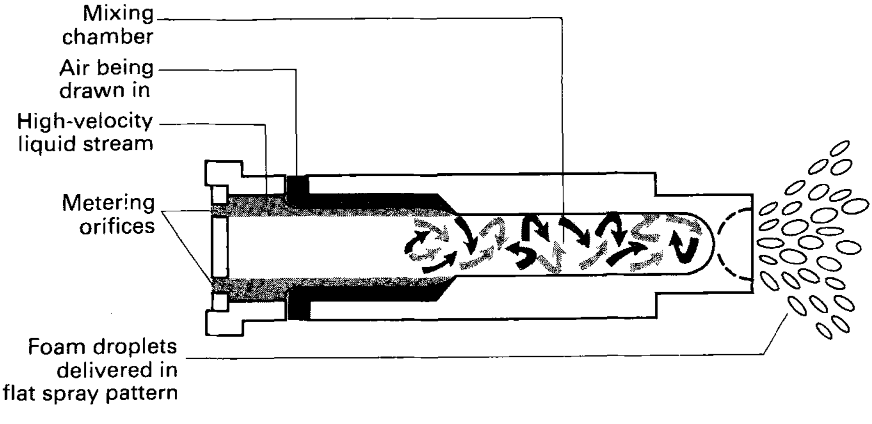


Fig. 5.15 Diagram of foam nozzle.

(Bouse *et al.*, 1976) were not followed by large scale use, but recently the need to have 'no spray' or buffer zones has led to greater use of air induction nozzles (see p. 14 and p. 116).

Intermittent operation of hydraulic nozzles

The idea of reducing the volume of spray applied from hydraulic nozzles by using a solenoid valve to provide an intermittent flow to the nozzle has been investigated previously, but has come into prominence in relation to precision agriculture. Giles and Comino (1989) described the control of liquid flow rate by positioning the nozzle directly downstream of the valve. A 10:1 flow turndown ratio (TDR) can be achieved by interrupting the flow while independently controlling the droplet spectrum by adjusting the pressure (Giles, 1997), but droplet size spectra were slightly affected over a 4:1 range in flow (Giles *et al.*, 1995a). The predominant effect of reduced flow was to produce slightly larger droplets, but the effect was so slight that the VMD was not significantly changed. Droplet velocity and energy were slightly reduced, as intermittency was increased (Giles and Ben-Salem, 1992). Changes in flow rate with pressure and duty cycle of the valve for an XR8004 (F80/1.6/3) nozzle is shown in Fig. 5.16, while the VMD is indicated for different flow rates in Fig. 5.17. The fitting of the solenoid allows a farmer to use one nozzle, e.g. F80/2.4/3, and apply flow rates down to the equivalent of a nozzle with half the flow rate at the same pressure. By adjusting the pressure from the cab, the user can change to a coarser spray while spraying near sensitive areas. Droplet spectra

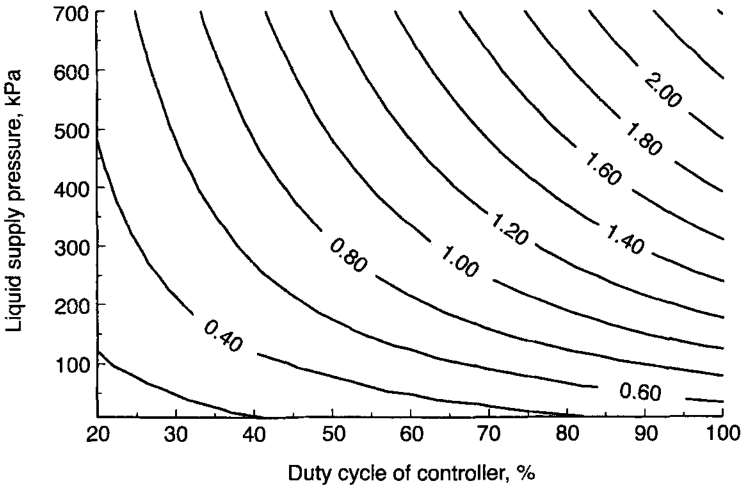


Fig. 5.16 Flow control envelope for XR8004 flat-fan nozzle from 70 kPa to 700 kPa liquid supply pressure and 20% to 100% duty cycle of valve. Isoquants are flow rates in litres per minute.

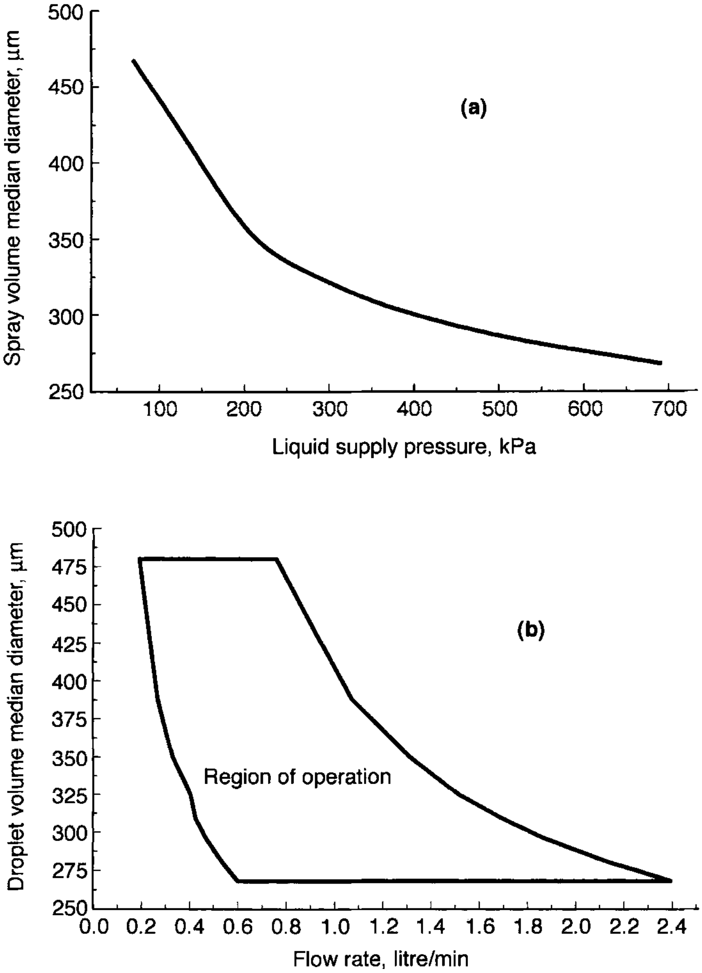


Fig. 5.17 (a) Volume median diameter of spray emitted from an XR8004 flat-fan nozzle over a range of liquid supply pressures from 70 to 700 kPa (Spraying Systems Co.). (b) Flow rate – droplet size control envelope for an XR8004 flat-fan spray nozzle over a liquid supply range 70–700 kPa and a valve duty cycle range of 20–100% (from Giles, 1997).

were affected if flow rate was decreased to 10%, and were generally more consistent with low flow rate nozzles than at higher flow rates (Ledson *et al.*, 1996).

Gaseous energy nozzle ('twin-fluid')

Some of the hydraulic nozzles have been adapted to become twin fluid nozzles in which air is fed into the liquid before it reaches the nozzle orifice. Other nozzles involving air shear are considered in Chapters 10 and 11.

With twin fluid nozzles, sometimes referred to as pneumatic nozzles, the spray quality will be affected by nozzle design, air supply pressure and spray liquid characteristics, e.g. viscosity and flow rate. In the 'Air Tec' nozzle (Fig. 5.18), air, fed into a chamber under pressure, is mixed with the spray liquid before emission through a deflector nozzle. This produces aerated droplets. By controlling both the air and liquid pressure, spray quality can be adjusted and low volumes applied per hectare with a relatively large orifice in the nozzle. Spray drift from this nozzle was significantly lower than that obtained from flat fan nozzles operated at 100 litres/ha (Rutherford *et al.*, 1989). This only applies if the nozzle is not used at too high an air pressure (> 10 bar) or very low flow rates (< 0.5 litres/min per nozzle) (Western *et al.*, 1989), otherwise drift could be exacerbated (Cooke and Hislop, 1987). Similarly, potential drift from the aerated droplets applied at 100 litres/ha was reported to be no greater than with conventional flat fan nozzles applying 200 litres/ha (Miller *et al.*, 1991). Subsequent studies indicated that in comparison with conventional low-volume fan nozzles, one design of twin fluid nozzle in a wind tunnel test produced drift intermediate between a standard fan and pre-orifice low drift nozzles (Combellack *et al.*, 1996). Womac *et al.* (1998) report similar assessments for the 'Air Tec', 'Air Jet' and another design 'LoAir' using water, a vegetable oil and mineral oils. They found that increasing the liquid flow rate

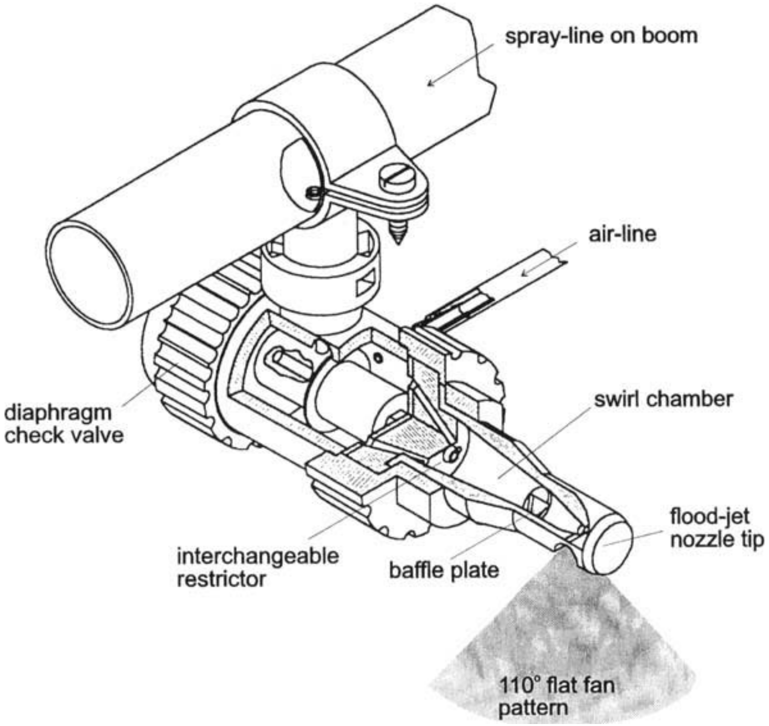


Fig. 5.18 'Airtec' twin-fluid nozzle.

increased the VMD and decreased the airflow, and that the proportion of small droplets (< 105 μm) was inversely and non-linearly proportional to the VMD. Atomisation of oils tended to produce small droplets and increased air pressure and flow rate also reduced droplet size, but in a way unique to each nozzle design.

Where sprays are applied at fast tractor speeds, there is a need to be able to adjust flow rate while maintaining a similar droplet size range. Combellack and Miller (1999) refer to nozzles needing a TDR of up to four. The TDR is defined as the difference between the lowest and highest flow rate divided by the lowest flow rate. Miller and Combellack (1997) also considered that a nozzle using less air volume and pressure was needed. The 'Air Tec' can require 25 litres of air per minute while a similar 'Air Jet' nozzle required up to 50 litres of air per minute. In practice the 'Air Tec' normally uses less than 10 litres of air per nozzle per minute, exceeding 10 litres of air per minute to achieve a fine or very fine spray at certain liquid flow rates. Subsequent work has shown that air consumption is reduced if air is delivered to a venturi nozzle insert where the greatest vacuum is produced, thus 5–8 litres of air per minute is sufficient (Combellack and Miller, 1999).

Kinetic-energy nozzle

A filament of liquid is formed when liquid is fed by gravity through a small hole, for example in the rose attachment fitted to a watering can, or the simple dribble bar, which can be used for herbicide application. The liquid filament when shaken breaks into large droplets.

Checking the performance of hydraulic nozzles

Calibration of flow rate

Flow rate or throughput of a hydraulic nozzle can be checked in the field by collecting spray in a measuring cylinder for a period measured with a stopwatch. Constant pressure is needed during the test period, so a reliable pressure gauge should be used. Output of nozzles mounted on a tractor sprayer boom can be measured by hanging a suitable jar over the boom to collect spray, but direct reading flowmeters are also available. Those fitted with electronic devices rely on battery power and need to be checked and calibrated. Throughput of nozzles at several positions should be checked to determine the effect of any pressure drop along the boom. The pressure gauge readings may require checking, as gauges seldom remain accurate after a period of field use. More accurate results can be obtained by setting up a laboratory test rig, with a compressed-air supply to pressurise a spray tank and a balanced diaphragm pressure regulator to adjust pressure at the nozzle. An electric timer operating a solenoid valve can be used to control the flow. The test rig should have a large pressure gauge frequently checked against standards and positioned as close to the nozzle as possible. The throughput of liquid, usually water, sprayed through the system can be measured in three ways:

1. in a measuring cylinder
2. in a beaker which is covered to prevent any losses due to splashing and the weight of liquid measured (Anon., 1971)
3. a suitable flowmeter can be incorporated in the spray line.

For gaseous, centrifugal-energy and other nozzles, flow rate can be determined by placing a known volume of liquid into the spray tank and recording the time taken for all the liquid to be emitted while the sprayer is in operation.

Spray pattern

Various patternators have been designed to measure the distribution of liquid by individual or groups of nozzles. An early design was described by Thornton and Kibble-White (1974). Liquid monitored through a flowmeter is sprayed from one, two or three nozzles on to a channeled table and collected in a sloping section which drains into calibrated collecting tubes at the end of the channels. Separation of the channels is by means of brass knife-edge strips, below which are a series of baffles to prevent droplets bouncing from one channel to another. Whether droplet bounce need be prevented is debatable, as nozzles are often directed at walls, the soil or other solid surfaces where bouncing occurs naturally. Spray distribution has been measured satisfactorily

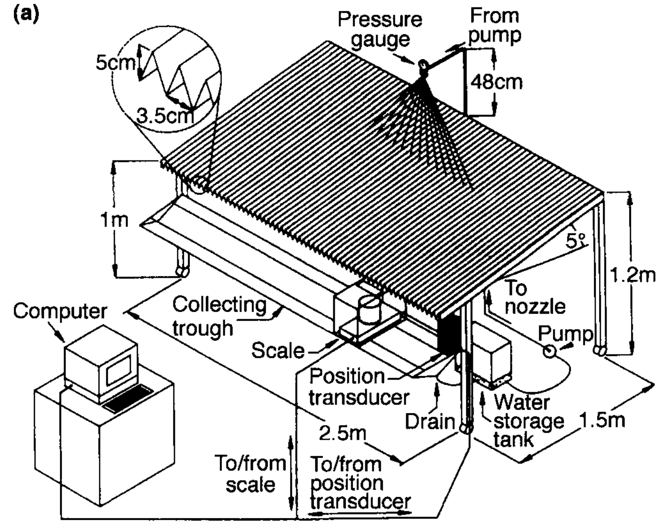


Fig. 5.19 (a) Automated spray nozzle patternator.

Fig. 5.19 (b) 'Spray scanner'.

with a simple patternator consisting of a corrugated tray. The nozzle is usually mounted 45 cm above the tray and connected to a similar spray line as that described for calibration of throughput. The standard width of each channel is 5 cm, although on some patternators each channel is 2.5 cm wide.

The main development has been in the way in which the volume of liquid in each collecting tube is measured. Patternators can now have a weighing system or an ultrasonic sensor that is moved across the top of each collecting tube and transfers data directly to a computer (Ozkan and Ackerman, 1992) (Fig. 5.19a). According to Richardson *et al.* (1986), the pattern can vary with successive runs with individual nozzles. Patternators can be positioned under a tractor boom to investigate variation in spray distribution along its length (Rice, 1967; Ganzelmeier *et al.*, 1994), and are now used to check the

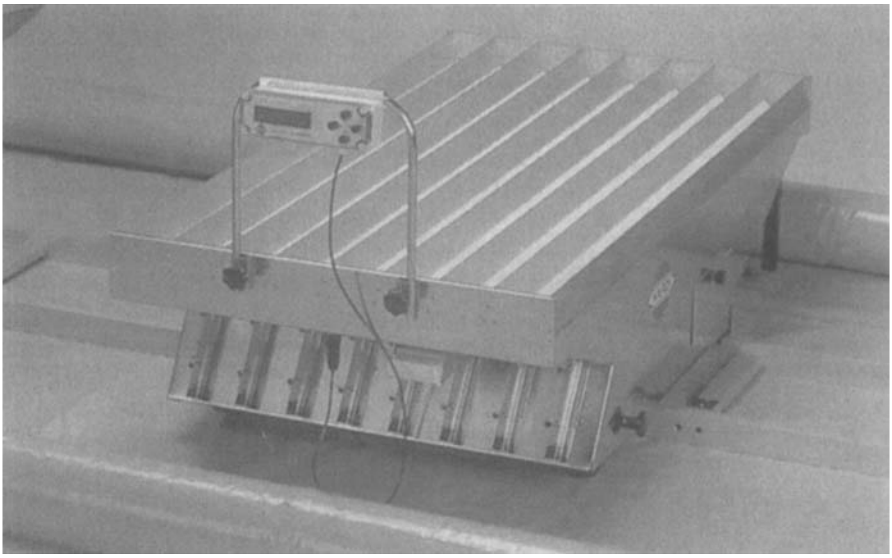


Fig. 5.19 (c) Close up of scanner.

performance of sprayers on farms. Another approach is to have a small number of channels on a trolley that moves along rails positioned under the spray. Data from this scanner (Fig. 5.19b) is downloaded to a PC.

Young (1991) used a two-dimensional patternator to assess the magnitude of a trailing plume from a stationary nozzle in a headwind, and thus assess the drift potential. Subsequently Chapple *et al.* (1993b) endeavoured to relate the pattern of a single static nozzle with the pattern obtained with a moving boom. Data from a patternator is mainly of relevance where spray is directed at a flat surface, but is less satisfactory for a complex crop canopy. In Germany, a vertical patternator was designed to assess the spray pattern from air-assisted orchard sprayers (Fig. 5.20) (Kummel *et al.*, 1991).

Nozzle erosion

The orifice of the nozzle tip is enlarged during use by the combined effects of the spray liquid's chemical action and the abrasive effect of particles, which may be the inert filler in wettable powder formulations or, more frequently, foreign matter suspended in the spray. This is referred to as nozzle-tip erosion and results in an increase in liquid flow rate, an increase in droplet size and an alteration in spray pattern. Increase in flow rate can result in over-use of pesticides and increased costs. This will occur especially where large areas are involved, so throughput should be checked regularly and the tip replaced when the cost of the cumulative quantity of pesticide wasted equals the cost of a replacement nozzle tip, if the rate of erosion is fairly regular (Kao *et al.*, 1972).

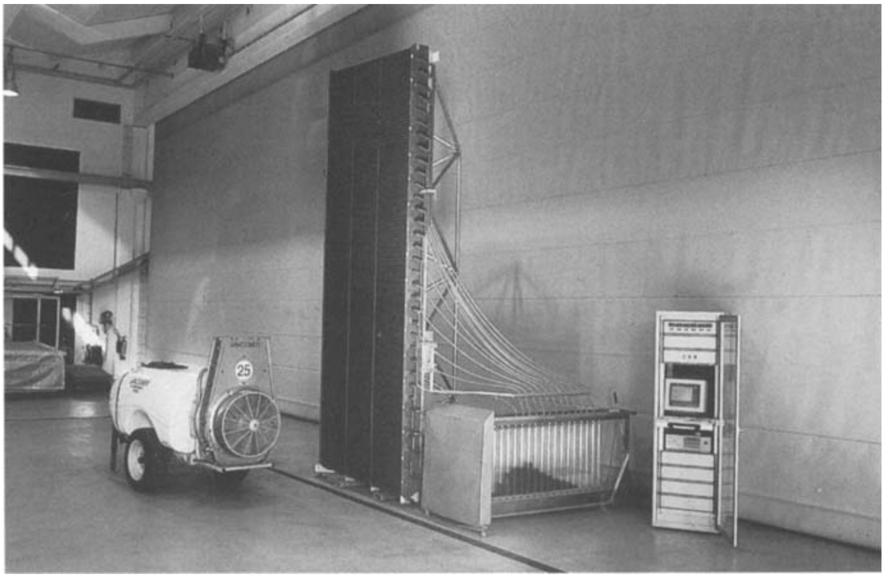


Fig. 5.20 Vertical patternator for orchard sprayer.

Rice (1970) reported increases in throughput of 49–63% with brass nozzle tips after 300 h wear with a 1% copper oxychloride suspension, whereas with stainless steel, ceramic and plastic tips, throughput increased only by 0–9% over the same period.

Over 70% of sprayers examined in a survey in the UK had at least one nozzle with an output that varied more than 10% from the sprayer mean. In extreme cases the maximum output was three times that of the minimum throughput (Rutherford, 1976). Beeden and Matthews (1975) and Menzies *et al.* (1976) have reported effects of erosion on cone nozzles. In Malawi, throughput increased by an average of 10% after 35 ha sprays, so a farmer should replace nozzle tips after three seasons. When water with a large amount of foreign matter in suspension is collected from streams or other sources, a farmer is advised to collect it on the day before spraying and allow it to settle overnight in a large drum. Nozzle tips should be removed after each spray application and carefully washed to reduce any detrimental effect of chemical residues. When cleaning a nozzle, a hard object such as a pin or knife should not be used, otherwise the orifice will be damaged (see Chapter 15).

Assessment of the effect of abrasion on a nozzle tip can be made in the laboratory by measuring the throughput before and after spraying a suspension of a suitable abrasive material. A suitable test is to spray 50 litres of a suspension containing 20 g of synthetic silica (HiSil 233) per litre (Jensen *et al.*, 1969; WHO, 1990), but other materials which have been used include white corundum powder which abrades nozzles similarly to HiSil but in onethird of the time. A test procedure for nozzle wear is also given by Reichard *et al.* (1990). Langenakens *et al.* (2000) showed by static and dynamic patternation that the quality of the distribution of worn nozzles was significantly worse.