

# Technical aspects of pesticide application

*A literature review*

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# Preface

Crop protection will also in the future remain an important aspect in crop production systems. Therefore an efficient use of chemicals is necessary as a result of a more direct application to the plants. This provides better coverage and prevention of emissions to soil, surface water and air.

In 1991 the Minister of Agriculture, Nature Management and Fisheries published the plan to reduce the use of chemicals in agriculture and their emission to the environment (Multi-Year Crop Protection Plan, 1991). In the framework of this plan an additional research program was started on application techniques with reduced emissions to the environment. The expertise of agricultural institutes and experimental stations is combined in this program.

The contribution of IMAG-DLO in this program is the research on development and use of detection methods and the introduction of new application techniques. Improved or new detection methods support the development of and research on new application techniques.

The present report contains a literature review of the aspects related to different aspects of application techniques. The report is the result of a co-operation of IMAG-DLO and the Department of Agricultural Engineering and Physics of the Agricultural University. The work accomplished by the authors Ms. J.C.A.M. Pompe, H.J. Holterman and B.C.P.M. van Straelen is gratefully acknowledged. A special word of thanks is directed to H.A.J. Porskamp for his comments and advice during the literature study.

The managing director  
A.A. Jongebreur

# Table of contents

<b>Preface</b>	<b>3</b>
<b>1 Introduction</b>	<b>6</b>
<b>2 Crop protection chemicals</b>	<b>8</b>
2.1 Types of pests and their chemical control	8
2.1.1 Pesticide formulations	8
2.2 Carriers and carrier volumes	10
2.2.1 Carrier volumes	11
2.3 Desired chemical distribution over the crops	11
<b>3 Crop protection application equipment and techniques</b>	<b>15</b>
3.1 Application equipment	15
3.1.1 Application equipment for field crops	15
3.1.2 Application equipment for orchards	16
3.1.3 Application equipment for greenhouses	17
3.2 Special techniques applied in crop protection	17
3.2.1 Row and band sprayers	18
3.2.2 Weed wipers	18
3.2.3 Intermittent spraying	19
3.2.4 Crop tilter boom	19
3.2.5 Air foil boom	20
3.2.6 Air-assistance	20
3.2.7 Recycling and Closed Loop Spraying Systems	22
3.2.8 Electrostatic spraying	23
3.2.9 Injection	24
3.2.10 Computerized dose control	26
<b>4 Drop formation</b>	<b>27</b>
4.1 Atomizers	27
4.1.1 Pressure atomizers	27
4.1.2 Air-liquid atomizers	28
4.1.3 Rotary atomizers and CDA	29
4.2 Spray angle of the atomizer and atomizer placement	30
4.3 Drop size, drop size spectrum and drop velocity	31
4.3.1 Drop size terminology	32
4.3.2 Factors affecting the drop size and the drop size spectrum	34
4.3.3 Drop size and crop protection efficiency	36
<b>5 Deposition</b>	<b>38</b>
5.1 Crop penetration	38
5.2 Impaction and adhesion	39
5.3 Retention, wetting and spreading	41
5.4 Distribution over the crop	42
5.5 Influence of sprayer boom movements	43

<b>6 Drift</b>	45
6.1 Application conditions and drift	45
6.1.1 Wind speed and drift	46
6.1.2 Temperature, relative humidity and drift	48
6.1.3 Crop morphology and drift	48
6.2 Application technique and drift	48
6.2.1 Drop size, drop velocity, drop direction and drift	49
6.2.2 Boom height, boom orientation and drift	50
6.2.3 Driving speed and drift	50
6.2.4 Application rate and drift	51
6.2.5 Air-assistance and drift	51
6.2.6 Electrostatic spraying and drift	52
6.2.7 Physical properties of the spray and drift	52
<b>7 Measuring techniques</b>	54
7.1 Measuring drop size, velocity and direction	54
7.2 Measuring spray distribution	55
7.2.1 Measuring spray patterns	55
7.2.2 Measuring spray deposits	56
7.3 Measuring emissions	57
7.3.1 Measuring drift	57
7.3.2 Measuring soil deposits	59
<b>8 Theoretical background</b>	60
8.1 Fluid mechanics of liquids	60
8.2 Fluid mechanics of air	61
8.2.1 Fluid mechanical considerations of air movement	61
8.2.2 Droplet transportation	62
8.2.3 Gravitational sedimentation	62
8.2.4 Entrained air stream	63
8.2.5 Atmospheric conditions	63
8.2.6 In-flight evaporation	64
8.2.7 Drop coalescence	67
8.2.8 Drop size and deposition	67
<b>Appendix a</b>	68
<b>Summary</b>	70
<b>References</b>	73
<b>Index</b>	80

# 1 Introduction

In view of the increased concern for the environment, the Dutch government aims to reduce the total consumption of crop protection chemicals with a minimum of 50% by the year 2000. To reach this goal, a research program has been started in which various research institutes cooperate. It is the challenge of the Institute of Agricultural Engineering to develop new techniques which result in reduced emission of crop protection chemicals. To have a sound base for this task, the literature on the technical aspects of chemical crop protection was reviewed. This review was carried out in co-operation with the Department of Agricultural Engineering and Physics of the Agricultural University of Wageningen.

The conditions under which the various cultures are protected against pests vary greatly. The result is that crop protection is performed in many ways:

- 1) some crops are sown, grown and harvested within a few months, while others have a lifetime of many years and are bare in winter, are fully covered with leaves in the summer and are in fruit in the fall;
- 2) their height can vary from 0 to 4 m;
- 3) the plant distance for some crops is a few centimeters and for others several meters;
- 4) planting patterns can vary from broadcast to rows;
- 5) different crops are hindered by different pests;
- 6) the environmental conditions vary greatly since crops are grown in the field or in greenhouses, where temperature, relative humidity, wind speed, etc. can be very different;
- 7) crops can be grown in soil, or in artificial media such as rock wool.

Each of these conditions has influence on the design of the plant protection application machines.

Pests can be controlled

- biologically (e.g. by predatory insects, bacteria or viruses),
- physically (e.g. by hoeing, stripping or pulling of foliage or flaming of weeds) or
- chemically.

This literature review is restricted to the third category: chemical crop protection.

Chemical crop protection can be applied

- through the air (spraying, fogging, dusting or gassing) or
- through the soil (soil disinfection, granular application of herbicides or herbicide injection).

These two different application pathways involve different processes. This review is restricted to chemical crop protection through the air from ground based equipment in moderate climates. Aspects not considered include aircraft spraying, seed and bulb treatment, crop protection during storage, trunk injection for trees, optimal spraying time with respect to pest development, occupational exposure and handling of the containers in which the chemicals were supplied. Literature on chemical application systems for protected cultures, as in greenhouses, was reviewed by the Glasshouse Crops Research Station in a separate study (van der Knaap and Koning, 1992).

This introduction is followed by two chapters which provide a short review on the pests which are being sprayed how and where; and on the equipment and techniques which are being used. The processes of drop formation up to deposition of the droplets on the target is reviewed in Chapters 4-6. Chapter 4 presents information on the way the various types of atomizers produce drops, in Chapter 5 the factors which play a role in air-borne emission (drift) of crop protection chemicals are reviewed, the process of deposition of droplets is discussed in Chapter 6. The techniques which are applied to measure sprays and their destination are reviewed in Chapter 7. Chapter 8 provides theoretical background on fluid mechanical aspects of the spraying process. This final chapter is followed by a glossary of terms which are used in the paper, and by a list of references.

# 2 Crop protection chemicals

## 2.1 Types of pests and their chemical control

Plant pests, and their chemical control, are classified into the following groups:

- nematodes, which are controlled with nematicides;
- insects and mites, which are controlled with insecticides and acaricides, respectively;
- fungi to be treated with fungicides;
- weeds to be controlled with herbicides.

All of these plant protection chemicals can reach their target via two basically different routes, namely 1) by direct contact or 2) after being taken up and transported through the plant. The first group is referred to as contact pesticides, the second as systemic pesticides. This difference may have implications for their application (see § 2.3).

The organized Dutch pesticide industry publicizes its turnover for the four mentioned groups of plant protection chemicals, yearly. Approximately 7% of the pesticides are sold by non-organized industry. The estimated total Dutch turnover of pesticides for the years 1985 through 1990 is shown in table 1. About 50% of the turnover is in the area of soil disinfectants. However, as pointed out in the introduction, soil disinfectants will not be discussed in this literature review.

**Table 1** Turnover of pesticides for agriculture and horticulture in the Netherlands, 10<sup>3</sup> kg active ingredient (from MJP-G, 1990).

Type of pesticide	1985/7	1988	1989	1990
Soil disinfectants	10,548	8,578	9,830	8,937
Insecticides/acaricides	564	575	745	731
Fungicides	4,003	4,147	4,052	4,140
Herbicides	3,895	3,639	3,330	3,468
Others	1,198	1,223	1,189	1,559
Total organized	20,244	18,162	19,146	18,835
Total Netherlands	21,500	19,400	20,500	20,200

### 2.1.1 Pesticide formulations

The formulation of crop protection chemicals can be varied. It depends on

- 1) the physical-chemical properties of the active ingredients and
- 2) the requirements posed by the various application techniques and machineries.

Crop protection chemicals are available as

- wettable powders (w.p.), spraying granules, suspension concentrates (s.c., also referred to as flowables), emulsifiable concentrates (e.c.), concentrate solutions (or soluble liquid, s.l.) all of which are usually mixed and sprayed with water;
- gas fogging formulations and aerosols, which are ready to be applied;



- dusting powders, granules and scatter materials, which are commonly applied in a dry form;
- smoke formulations, evaporators, etc. which apply the active ingredients as vapors in a confined space.

The active ingredients are often available in more than one formulation. Each formulation is effective for its specific application (MJP-G, 1990).

The main factors which affect the choice of formulation are

- the properties of the pesticide,
- the impact of formulation type on biological expression and
- the handling of the product by the farmer.

Chemicals which are soluble in water in their own right or as salts offer a simple way for formulation as soluble concentrates. Liquid pesticides which are immiscible in water can normally be formulated as emulsifiable concentrates, while solid pesticides can be produced as wettable powders. Solids which have low solubilities and are chemically stable in water can be formulated as suspension concentrates, which are dispersions of fine particles of the pesticide. Water-dispersible granules are an alternative to wettable powders and are much safer and easier to handle as they are free flowing and free of dust (Southcombe and Seaman, 1990).

Emulsifiable concentrates consist of the liquid pesticide, solvents and emulsifiers. Solids which are sufficiently soluble in solvents can be formulated in this way also. When added to spray water, fine emulsions are spontaneously formed, giving a droplet size of only a few micrometers. As the chemical is in solution in a lipophilic solvent, it is readily available to penetrate leaves, so emulsifiable concentrates can be a highly active presentation. An alternative to emulsifiable concentrates for liquid pesticides which are chemically stable in water, is as a preformed emulsion. This form reduces or removes the solvent component and can reduce the dermal toxicity of the formulation.

Suspension concentrates are suitable for pesticides which have a solubility in water below a few hundred parts per million and which are chemically stable in water. To prevent settling of the fine particles (<5  $\mu\text{m}$ ), which could form a compact sediment, anti-settling agents are added. The finer particle size compared with wettable powders can lead to greater biological activity (Southcombe and Seaman, 1990).

The choice of formulation mainly depends on two physical properties: the melting point and the solubility of the active ingredient. It is easier to provide a reliable and quick formula for the emulsifiable concentrate than for the wettable powder or suspension concentrate, provided the solubility and chemical stability permit this (Hartley and Graham-Bryce, 1980). The authors presented an extensive textbook of the physical principles of pesticide behavior. Included in the textbook is an overview of the physical properties, such as molecular mass, melting point, solubility, vapor pressure, saturation vapor concentration, and ionization coefficient of many common pesticides.

Wash-off by rain can be reduced by using pesticide formulations with lower water solubility. Wash-off can also be decreased by using finer suspensions, since smaller particles adhere stronger (Tadros, 1987).

Most herbicides have a relatively low vapor pressure. This is also true for ester-based herbicides except for ester-based hormones. These latter ones are characterized by high vapor pressures, and with that pose a risk of damage. This type of herbicide is commonly formulated in combination with salt-based hormones.

Physical properties can be affected by the addition of adjuvants. These adjuvants are added to the formulation to improve the biological effect of the pesticide. They can be added as an integral part of the formulation, or added to the spray tank. The most common adjuvants are surface-active agents, commonly called 'wettters' or 'wetting agents', and oils.

Wetting agents are detergent-like chemicals. They reduce the surface tension of the solution, increase the solubility of the pesticide and solubilize the wax on the leaf surface. This enhances 1) spray retention, 2) spreading of the deposit and 3) uptake of the pesticide through the leaf cuticle (Southcombe and Seaman, 1990; Tadros, 1987). Oils have similar effects, but less is known about their mode of action.

Other ingredients are added with the purpose to reduce drift and evaporation of the pesticide. Drift retardants ideally reduce the number of very small droplets, without increasing the number of very large droplets (see also § 6.2.7). Evaporation retardants increase the viscosity and reduce the surface tension (see also § 4.3.2) (Schmidt, 1980).

## **2.2 Carriers and carrier volumes**

Hartley and Graham-Bryce (1980) enumerated a number of, sometimes conflicting reasons why carriers are used for the dispersal of pesticides.

- The transport of pesticides from the factory to the farm requires a small container, while the product needs to be distributed over a large area.
- Pesticides must be aimed to the crop and/or ground rather than onto a wider environment. Use of a carrier makes it possible to spray in larger drops, which adds momentum and reduces undesired emissions to the air.
- Larger mass and volume increases the visibility of the spraying process, so that the operator can see how the machine is performing.

The disadvantage of the use of a carrier is that it increases the weight which needs to be carried.

The following three carriers are used:

- 1 Water
- 2 Forced air
- 3 Oil

The most commonly used carrier is water. Forced air is frequently used in combination with water.

Oil is non-volatile and prevents the evaporation of small droplets. However, oil-based formulations can only be sprayed with special equipment such as ULV/CDA (Bals, 1983) (see also § 4.1.3). Mineral oil is the most commonly used type of oil, but vegetable oil is less costly and can also be applied as an additive or complete carrier.

### 2.2.1 Carrier volumes

Large volumes of the carrier, whether it be water or air, serve to penetrate the crop canopy. Most pesticides are sprayed as liquids, in volumes which range from several hundred liters per ha down to several liters/ha. The total application rate of the active ingredient is more or less constant, so that the concentration of the active ingredient is increased proportionally with a decrease in volume rate.

Different cultures are sprayed with different application rates. This has led to the misleading practice of using identical terminology for different application rates in arable crops and in orchards (see Table 2).

**Table 2** Classification of application rates for arable crops and for orchards.

	Application rate, l/ha	
	Arable crops <sup>1</sup>	Orchards <sup>2</sup>
High Volume (HV)	> 600	> 1000
Medium Volume (MV)	200-600	500-1000
Low Volume	50-200	200-500
Very Low Volume (VLV)	5-50	5-200
Ultra Low Volume (ULV)	0.5-5	< 5
Ultra Ultra Low Volume (UULV)	< 0.5	-

<sup>1</sup> (Eckert, 1987)

<sup>2</sup> (OEPP, 1982)

The application rates which are achieved in the field often differ greatly from the intended application rate. Matthews (1977) warned against the detrimental effects on the ecosystem caused by excessive runoff which can result from high volume spraying. Errors of 60% underdosing and 90% overdosing were quoted by Han, *et al.* (1986). Hislop (1987) concluded that there is little biological advantage in using volumes greater than 500 l/ha. When volumes are reduced below 100 l/ha, disease control may decrease, probably as a result of reduced coverage rather than reduced deposition.

Bouchet (1983) evaluated the effect of reduced application rates on the effectiveness of herbicide and fungicide treatments. He concluded that herbicide treatments with flat fan nozzles were all nearly as effective at rates down to 75 l/ha, provided that basic conditions (dose, crop stage, etc.) were suitable for spraying. The efficacy of the lower volumes was lower as soon as the spraying conditions were not ideal. He also concluded that the results with centrifugal spraying ('Girojet') at rates down to 25 l/ha were similar for fungicide treatments in cereals, but variable for herbicide treatments in cereals and much lower for herbicide treatments in beets.

### 2.3 Desired chemical distribution over the crops

The optimum degree of coverage in any spray application depends on the mode of action of the pesticide and the nature of the pest to be controlled. Contact pesticides need to be applied in such a way that they leave a long-lasting deposit or such that they are transferred locally within the crop through slow evaporation. Systemic pesticides

should form a residue which can penetrate the cuticle (Tadros, 1987). The character of the deposit may be influenced by the physical natures of the pesticide, of the carrier, and (if applicable) of additives.

With contact pesticides, the mobility or location of the pest determine the required extent of cover. The more static the pest, the greater is the need for complete coverage of the plant areas which are liable to be attacked. Predators and parasites which contribute to biological control are generally considerably more mobile than the pests which they attack. Treatments should be designed to minimize damage to such beneficial insects (Hartley and Graham-Bryce, 1980).

On the other hand, systemic pesticides provide a satisfactory cover when the spray is deposited on those areas of the plant through which the pesticide is absorbed (Tadros, 1987). Often only the younger foliage is susceptible to pests or diseases (Hislop, 1987), while it appears that the uptake of chemicals into monocotyledonous plants is usually greater near the leaf base (Last and Parkin, 1987).

Underdosing should be avoided since it carries the danger of inducing resistance to the pesticide. This is also true for local underdosing (Hall, 1987). Overdosing creates unnecessary burdens on the environment.

### *Insecticides and acaricides*

Insects can pick up insecticides from leaves and twigs. They can also collect small droplets directly, which gives a very effective control. The effectiveness of spray applications varies greatly between different types of insects. Easily controlled insects include those which move to exposed surfaces. Others are more difficult to control since they hide on the lower leaf surface (e.g. whitefly nymphs) or enter the plant immediately after the eggs hatch (e.g. stem or fruit borers). Such pests are commonly controlled with an ovicide in the egg stage. Granule formulations were more effective in the control of the maize stem borer, *Busseola fusca* (Fuller), because the particles fell inside the 'funnel' to where larvae start penetrating the stem, whereas spray droplets cannot reach such a zone. Several insects are most efficiently controlled by spraying during the evening, not only because the weather conditions are more favorable, but also because the insects are more active during this time of day (Matthews, 1977).

Hislop (1987) discussed the seemingly contradicting results of experiments on number of droplets and pesticide concentration on mortality of mites. He suggested that for a give dose per area, high volume rates may result in a more uniform coverage. This could prevent underdosing and thus result in higher mite mortality, despite decreased total pesticide deposits.

Several pesticides may change the behavior of their targets, like causing migration without direct mortality. Different combinations of concentration, droplet sizes and distributions may have different effects (Hall, 1987; Hislop, 1987).

Many pests reside preferably on specific parts of their hosts. This could mean that control

of these pests is most effective if it is aimed at those locations. The adults of the glass-house whitefly *Trialeurodes vaporariorum* reside almost exclusively on the undersides of the leaves, while this insect deposits her eggs preferably on the youngest, topmost, leaves of glass-house crops (Adams, et al., 1987).

Adams and Lindquist (1991) refer to research in greenhouses which demonstrated that bifenthrin can irritate and kill the aphid *A. gossypii* without the presence of a spray deposit. Hislop (1987) concluded that this was the result of the vapor activity associated with very fine droplets.

Hartley and Graham-Bryce (1980) deduced a theoretical relationship between the size of an insect and the pesticide dose which it will receive by vapor transfer and by direct hit. They calculated the pesticide dose which spherical insects with a radius of 1 mm and 5 mm will receive. They concluded that the smaller insects would receive doses which are 50 and 5 times as high by vapor and direct interception routes, respectively. They suggested that this difference can be used for selective spraying between pests and their natural enemies which are often much larger.

### *Fungicides*

Systemic fungicides are preferably absorbed by the roots: root applications are most effective. In rock wool cultures systemic fungicides can be added to the feed solution, while in rice cultures they can be applied with the irrigation water. However, the possibilities for root application in soil based cultures are limited and systemic fungicides are most commonly applied via the leaf.

Even pests which attack older parts of the plants, may be controlled effectively by applying pesticides to younger plant sections. Eyespot of wheat occurs at the stem base of the plants. This fungus was controlled more efficiently with CDA applications (see § 4.1.3), which deposited concentrated low volume sprays (10 l/ha) on the upper parts of the wheat canopies, than with the higher volume (103 and 206 l/ha) applications (Cooke and Hislop, 1987). The authors suggested that this may be a result of a redistribution by rain and/or dew of the highly concentrated active ingredient from the site of deposition to the soil/stem interface over an extended period.

Vapor action of fungicide deposits can play an important role in fungus control, especially in protected environments such as greenhouses (Hislop, 1987).

### *Herbicides*

Western and Woodley (1987) suggested that distribution of spray deposits between different parts of treated plants or the pattern of deposition over the plant surface may be more critical in weed control than total deposition. Many herbicides are preferably taken up via the leaf sheath, petiole or stem. The leaf sheath is also a very effective site for the uptake of systemic fungicides. When substantial quantities of the herbicide phenmedipham were washed off by light rain from *Veronica persica* seedlings, increased quanti-

ties were recovered from the petioles and stems and herbicide activity was increased (Hislop, 1987).

Hess and Falk (1990) concluded that the optimal distribution of an herbicide would be a thin layer over the entire sprayed leaf surface. This should preferably be in liquid form or in true solution, as opposed to a crystalline herbicide adhering to a particle matrix (wetable powder).

# 3 Crop protection application equipment and techniques

In order to place the behavior and measuring techniques of pesticide spray into the full context, in this chapter a review of the common spray equipment and spraying techniques is given. Similar spraying techniques are used on equipment of very different configuration. Therefore the equipment the application techniques are discussed in two separate sections.

## 3.1 Application equipment

The crop protection equipment for field crops, for orchard crops and for greenhouse crops are configured differently as a result of the different crop morphology and of the conditions under which they are grown. Koch (1989) reviewed typical application parameters such as application rates, spray direction and boom heights for a number of cultures (Table 3).

**Table 3** Typical application parameters for various cultures (modified from Koch, 1989).

Implement/area of application	Typical application rate (l/ha)	Flight direction of droplets	Distance nozzle-target (m)
<i>Field sprayers</i>			
– Arable crops	200- 400	downward	0.5-0.8
– Vegetables	400-1000	downward	0.5-0.8
<i>Spray blowers</i>			
– Fruit	250-1500	horizontal-upward	1-5
– Grapes	250-1000	horizontal-upward	0-1
– Hops	700-3000	horizontal upward	5-8

### 3.1.1 Application equipment for field crops

Application equipment for chemical pest control in field crops can be divided roughly into:

- field crop sprayers (including row and strip techniques, see § 3.2.1);
- weed wipers (see § 3.2.2).

Spraying devices can be tractor-mounted, tractor-trailed or self-propelled. The sprayer tank volume of tractor mounted sprayers range from 200-1000 liters. Tractor trailed sprayers are supplied with tanks with a capacity of 1500-2000 liters and have booms of up to 24 m wide, which is conventional in the Netherlands.

Spraying devices usually consist of an identical set of parts. Current field crop sprayers can be equipped with the following parts:

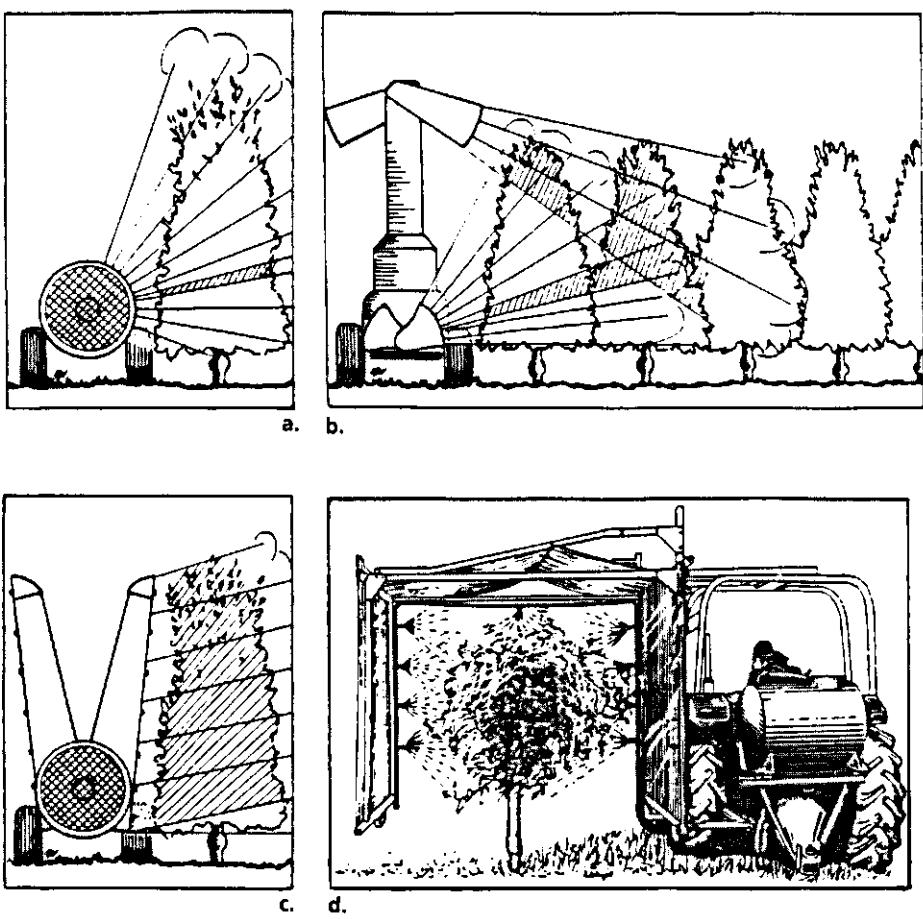
- multiple nozzle holders provided with the appropriate nozzle types of low-wear material;

- a sprayer boom divided into parts each of which can be closed individually from the tractor seat;
- a stable sprayer boom which is height-adjustable;
- a flow and/or pressure control unit;
- a measuring device for the driving speed, connected to a computerized unit for dosage control.

Row and strip sprayers are basically regular field crop sprayers with modified nozzle placement and/or nozzle shielding (see § 3.2.1 for detailed information).

### 3.1.2 Application equipment for orchards

Spraying in orchards is usually carried out with air-assisted spraying equipment. Conventionally an axial ventilator is used, spraying the droplets radially outward.



**Figure 1** Various types of orchard sprayers:  
 a. conventional sprayer with axial fan, b. conventional sprayer with 'tower sprayer',  
 c. cross flow sprayer with vertical boom, d. screened tunnel sprayer (from: Wiedenhoff, 1986; IKC, 1990).



Special developments include (see Figure 1):

- a ‘tower sprayer’ for cultures with 5 to 7 row. This consists of a special spraying device which reaches out over the crop. This spraying device is mounted on a conventional sprayer;
- a cross flow sprayer with vertical boom. During the last decade the conventional sprayer has been improved by mounting the air-outlets on a vertical device so that the spray is applied horizontally to the crop. This improved the distribution of drops over the crop, while drift was decreased (Wiedenhoff, 1986);
- screening of the sprayers and recycling devices to prevent wind effects and to enhance spraying process efficacy (van de Werken, 1991a, 1991b).

Several aspects may affect the efficacy of spraying:

- the distance between nozzles along the vertical sprayer boom, in relation to the height of the crop and the crop density;
- the position of the nozzles in relation to the air-outlet;
- the direction and velocity of the air stream.

It is noteworthy that the vertical booms of some sprayers roughly follow the contours of the crop.

### 3.1.3 Application equipment for greenhouses

Compared to open field conditions, greenhouses provide environmental conditions that are more stable and controllable. Pesticide sprays applied under glass are physically contained, which essentially should eliminate emissions to the air, while air movement may be controlled. This means that droplets as small 20-30  $\mu\text{m}$  may be applied (Adams, *et al.*, 1987; Adams and Lindquist, 1991).

As a result in greenhouses various alternative techniques are used for applying crop protection chemicals besides spraying. Examples are: gassing, dusting and/or fogging. The materials are applied in such a way that the droplets or small particles remain suspended in the air for a long time, without precipitation on the crop. Before the grower reenters the greenhouse he vents it, so that the remnants of the suspended droplets or smoke particles will leave the greenhouse.

In this context it is important to realize that even closed greenhouses exhibit natural ventilation rates of 50-100% of the greenhouse air per hour. A second important aspect is the condensation of pesticides on the greenhouse cover. The condensed pesticides may run-off or may be collected in condensation gutters. Emission of pesticides from greenhouses was estimated to amount 5-10% of the applied quantities (MJP-G, 1990).

In a separate literature review, the Glasshouse Crops Research Station reviewed the crop protection equipment for greenhouses (van der Knaap and Koning, 1992).

## 3.2 Special techniques applied in crop protection

Several special techniques are used to enhance application efficiency. Roughly these

techniques can be divided into three categories: application techniques (§ 3.2.1 through § 3.2.3), application tools (§ 3.2.4 through § 3.2.8) and dose control systems (§ 3.2.9 and § 3.2.10).

### 3.2.1 *Row and band sprayers*

Row sprayers restrict the spraying to the row in order to reduce the pesticide consumption. Band sprayers are used to control weeds in the area between the rows without damaging the crop.

Row sprayers can reduce pesticide consumption in row crops by spraying only in the crop row, while leaving the inter-row areas untreated. Row spraying can be applied to control fungi, to kill potato leaves, or to treat weeds in the row. Such a treatment could be combined with mechanical control of the inter-row area, like for instance hoeing in the case of weed control. The individual nozzles are arranged to cover a strip only a few centimeters wide, commonly 18 cm (Southcombe and Seaman, 1990). The swath width of row sprayers needs to be well-defined to ensure that sufficient pesticide solution reaches the row and its edges. This can be achieved best by using special flat fan nozzles (Even-spray nozzles) (see § 4.1.1) which were developed for this purpose. Drift potential of these nozzles is low mainly because of the low boom height above the crop. Evidently, the nozzles must be placed over the swath center and at a constant height. Variations in the nozzle height result in a narrower or wider swath width, which results in local over- and underdosing, respectively. In order to maintain a constant swath width, the nozzles need to follow uneven spots in the soil. This can be achieved with the aid of skid shoes or on a running wheel attached to the spraying boom by a parallelogram. The effect of the variations in the nozzle height on the swath width can be reduced by mounting the nozzle with an angle of 45° with respect to the driving direction. Sometimes a triangular-type deposit pattern is preferred to reduce the dose along the edges of the band where it overlaps the hoed ground.

Band sprayers (also called strip sprayers) can be applied to spray herbicides between rows. 80-90% of the total area is usually covered by strip sprayers. Non-selective herbicides are often sprayed with this type of equipment. Placement of shields or hoods over the nozzles makes it possible to spray very close to the rows, while avoiding spraying the row crop by lifting its foliage.

For wide-spaced orchard trees, nozzles have been arranged on swinging arms to treat circles around the tree base which is protected by a U-shaped shield (Southcombe and Seaman, 1990).

### 3.2.2 *Weed wipers*

Weeds which extend over the crop and which can only be controlled with non-selective herbicides, can be treated selectively by touching the tops of the tall weeds with an herbicide with the aid of a weed wiper. Techniques which are available include: moist sheets which are fed by capillarity, wicks fed by capillarity, charged wicks and pressure-

fed wicks. Weed wiping 1) requires very low application rates (2-6 l/ha), 2) is possible under windy conditions, 3) is very simple and 4) low in cost. However, Morel (1983) concludes that the technique shows promise in prairies, but that in beets too many low weeds remain, resulting in unacceptable yield reductions.

Non-selective herbicides applied with weed wipers in grassland may severely damage the grass, either by direct hit or after contact with treated foliage. In order to prevent such damage Oswald (1985) applied a selective herbicide with a rope wick applicator below the grass canopy. He concluded that the grasses were not damaged and that this approach was more effective than rope wick applications of a non-selective herbicide applied above the grass canopy. The author cautioned against rope wick applications at ground level, since this would require uneconomical large amounts of herbicide, and would pose the risk of the rope wick drying up in dense swards or the flow of herbicide being impeded by loose plant material.

### 3.2.3 *Intermittent spraying*

Giles, et al. (1988) developed an electronic sensing system with ultrasonic transducers to detect the tree canopy and measure its extensions. Tree extensions could be measured with less than 10% error and with good repeatability. Driving speed (2, 4 and 6 km/h) did not affect the results significantly.

Development of control systems for sensing of target characteristics and optimization of spray output has been studied by Giles and BenSalem (1990). They did theoretical and experimental investigations on the spray droplet dynamics within intermittent spray clouds. Electrical solenoid valves were excited at a frequency of ca. 10 Hz and duty cycles of 10 to 70%. Flow turndown ratios of 3.5 to 1 could be obtained. Distortion of droplet size spectra and spatial distribution of spray liquid was relatively small in the case of flat fan nozzles.

Göhlich and Westphal (1991) expect that in the future the spraying process can be adapted based on information from sensors which detect the presence (or absence) of the target surface, or which determine the local characteristics of the crops such as the plant contours or crop density.

### 3.2.4 *Crop tilter boom*

Göbel and Göhlich (1989b) describe a crop tilter boom, which improves penetration of the spray liquid into cereal crops. The tilter is mounted on the boom, in front of the nozzle. The boom, which is passed at 0.05 m over the crop tilts the cereal halms forward just before the nozzle passes over them. While passing under the nozzle the halms move back to their original position in a fan shape manner. By varying the spraying direction, the pesticide spray can be aimed at the ears, at the leaves or at the halms of the plants. The spraying direction can be varied by mounting the nozzles with a rearward angle or by applying revolving nozzles. The crop tilter boom was found to reduce emissions to the air by 70 to 90%. Ripke (1990) found that the crop tilter reduced emissions to the air but increased pesticide emissions to the ground.

### 3.2.5 *Air foil boom*

An air foil or aerofoil above the spray boom of a field sprayer directs the pesticide spray more into a field crop so that the creation of a spray cloud is limited. The implement consists of two metal profiles which are bent downward, so that the air, which approaches the profiles horizontally, is forced downwards between the two plates. The space between the two profiles narrows as the curve increases, so that the air is accelerated. A nozzle is mounted right under the beginning of the lower profile. An air foil boom would reduce ground deposits, since the retention of the droplets on the plants is increased by the additional air turbulence created by the air foil (Göhlich, 1985). Using an aerofoil Miller (1988) mentions airborne reductions of more than 60%. Use of an air foil would reduce emissions to the air by some 25-40% (Göbel and Göhlich, 1989b). The performance of an aerofoil is affected by wind direction since travel and wind speeds are often of a similar magnitude. The complete boom has also been shrouded in order to prevent disturbance of the spray sheet by wind and air movements associated with forward travel. Such a shroud needs to be designed in such a way that the creation of a low pressure area immediately behind the boom is avoided. Otherwise small air-borne spray droplets would be drawn from beneath the shroud and still cause emission hazards. Such shrouded systems increase the weight and complexity of the boom structure and no commercial machines of such type had been developed in the UK in 1988.

### 3.2.6 *Air-assistance*

While air-assistance has long been used in orchard spraying, it has only recently been introduced in field crop spraying. The air can be used to direct the spray droplets to the target. Improved penetration of the crop is the main goal. In air-liquid atomizers air-assistance serves a different role: here it is used to improve the atomization quality or to increase the range of the flow rate of the nozzle; see § 4.1.2).

The design of air-assisted sprayers differs in

- placement of the nozzle with respect to the air flow;
- type of fan.

#### *Placement of the nozzle with respect to the air flow*

The spray nozzles can be placed in or out of the air flow. Placing the nozzles in the air flow may affect spray droplet distribution. The alternative is to place the nozzles such that the droplets enter the air flow from the side. The spray nozzles should be placed outside the air stream to allow the drops to be evenly distributed before entering into the air flow.

#### *Fan types*

Generally, three types of fans can be distinguished:

- axial fans;
- radial (or centrifugal) fans;

– tangential (or cross-flow) fans.

Fan characteristics are described in detail in Appendix a.

Because of their low air volume output with respect to the air velocity, radial fans are usually not suitable for air-assisted spraying. Its usage is limited to sprayers with individual air ducting to all nozzles, because high back pressures occur in those situations (Miller and Hobson, 1991). With field crops, mostly axial fans are used for air-assistance.

The gradual air velocity loss with increasing distance from the fan outlet is much lower for tangential fans than for the other fan types. The air velocity loss increases with increasing driving speed, due to speed induced turbulence at the air stream circumference (Rosswag and Moser, 1987). With orchard crops, therefore, penetration into dense foliage cannot be achieved using a tangential fan. However, with respect to the evenness of the air velocity profile a tangential fan is recommended. In practice both axial fans and tangential fans are used in orchard spraying.

#### *Air-assistance for field crops*

The transport of air from the ventilator to the nozzles is usually achieved via a wide duct, which is slotted or perforated at distinct intervals. An evenly distributed air flow along the duct length of perforated or slotted ducts can be achieved using a tapered duct with one end closed (Miller and Hobson, 1991). Ducts of constant cross-section have a relatively low air volume output through holes near the duct entrance and a high output through holes near the opposite end.

The nozzles of the 'Degania' sprayer are placed underneath a perforated duct in the air flow. This narrows the spray width which renders it necessary to decrease the distance between the nozzles considerably (Hadar, 1991). Other systems, such as 'Hardi Twin' and 'Kyndestoft', have the nozzles placed in front of the air curtain. They maintain the traditional nozzle distance (see also § 4.2).

Hadar (1991) found that air-assisted sprayers work well with all kinds of nozzles and application rates, however, he achieved best results with cone jet nozzles, since these showed fewest clogging problems.

#### *Air-assistance for orchard crops*

Lind (1989) pointed out that crop density in orchards varies with height. In order to deal with this problem the individual nozzle distances to the canopy should be adjusted while using only one type of nozzle. Crop density variation also requires an adapted air stream profile. An air flow perpendicular to the driving direction is appropriate only for high foliar densities and large row distances. In vineyards, however, a perpendicular air stream is usually too powerful because of the relatively low crop density and thus low resistance to air passing through. Deposition can be improved by directing the air stream slightly backward, since in this way the air has to travel a longer path through the canopy. However, the driving speed should not be too high in this case.

Another possibility is to use a dual-air stream, one directed slightly forward, the other directed slightly backward. The induced air pressure drop between the two air streams stabilizes the dual-air stream profile and enhances turbulence, which improves deposition in the canopy.

Generally, in vineyards a wide low-velocity air flow is more suitable than a narrow high-velocity air flow.

Wiedenhoff (1986) recommends for orchards to direct the air flow from cross-flow type sprayers slightly upward (approx. 12°) and slightly backward (approx. 15°).

To reach the top of the plants in orchards and vineyards with axial fans, the air stream must be directed steeply upward. Thus a large amount of spray overshoots the plant and drift is enhanced. Additionally, in axial fan sprayers the air velocity profile depends on fan rotation direction and is therefore not equal on both sides of the orchard sprayer (Bäcker, 1986).

### 3.2.7 *Recycling and Closed Loop Spraying Systems*

Ladd, et al. (1984) designed a recirculating field sprayer for sweet corn. The spray was applied horizontally to the crop. The excess of spray not reaching the plant was caught by a collector, and after filtration redirected to the spray tank. At an application rate of 700 l/ha conventionally, 30% to 35% spraying liquid could be saved using the recirculating sprayer.

Bäcker and Rühling (1991) described recycling systems for vineyard spraying involving a reflector surface or a collector surface. With the reflector system, the transport of the spray is assisted by an air stream generated by a tangential fan. The air stream penetrates the target object, strikes against the reflector surface, where it deflects back in the direction of the target object. The portion of the spray which has not struck the plant, precipitates almost completely at the reflector surface, where it is transported back to the supply tank. A minor residual portion is drawn by the deflected air stream back to the target where it has a second chance to settle.

With the collector system, the collector surface consists of vertically arranged separation profiles used for separating liquid particles out of the air stream. Like the reflector surface, the collector surface is placed behind the target object. This collector can be used with any vertical fan.

Recirculation efficiencies of up to 70% for both systems could be obtained.

Nordby (1989) described a closed system which is employed for spraying trays with forest seedlings. The bottom of each tray is cleaned with brushes, after which the trays are conveyed through a chamber. The spraying takes place in this chamber. Approximately 25% of the spray is deposited on the plants, and the excess of spray is filtered and returned to the spraying tank.

Recently a tunnel sprayer was developed for unmanned operation in orchards (van de Werken, 1991a, 1991b). The sprayer incorporates the 'Closed Loop Spraying' (CLS) system

in which the spray filled air inside the tunnel is recirculated and used for air-assistance. In about 7% (with a dense foliage) to 30% (with bare trees) of the sprayed liquid was regained by the recycling system (Porskamp and Beerens, 1991). The system was adapted for use as a tractor-pulled sprayer (van de Werken, 1991b).

### 3.2.8 *Electrostatic spraying*

Electrical charges in pesticide spraying is used for two different reasons, i.e.:

- to create droplets;
- to enhance spray deposition.

Normally, a spray liquid is electrically neutral, since positively charged protons are balanced by negatively charged electrons. When a spray is electrostatically charged, this normal balance is disturbed by transport of electrons. A shortage of electrons makes the fluid positive and vice versa. A spray droplet can carry a maximum charge (the Rayleigh limit). When the external electrostatic pressure exceeds the binding surface tension electrostatic drop shattering occurs.

Three methods can be distinguished to atomize drops using electrical charges:

- corona charging or ionized field charging;
- induction charging;
- contact charging, direct charging or electrodynamic charging.

Corona charging or ionized field charging employs a needle held at a positive high voltage to charge the liquid which is directed past the end of the needle. This method requires the use of very high voltages in order to ionize the air surrounding the liquid. The high electrical field necessary for ionization is usually obtained by raising a pointed electrode to a voltage in excess of 20 kV, and as high as 70 kV (Marchant, 1980; Ganzelmeier and Moser, 1980). With the high voltages used the isolation of the liquid in the tank from the sprayer frame presents a problem.

Induction-charging employs a high voltage electrode close to where the spray liquid is emitted from a nozzle and breaks into droplets. The system requires a good conductor such as water, and is not suitable for poor conductors such as oil.

Since the polarity of the spray droplets and of that of the electrode is opposite, some droplets are attracted to the electrode. This creates the danger of wetting the electrode and a short-circuiting of the power supply. This problem is avoided by adding an air stream to the nozzle (Matthews, 1989).

Marchant (1985) described a method for induction charging the spray from a spinning disc atomizer where both the atomizing disc and the electrode rotate. This prevents the deposition of the spray on the electrode which reduces the chance of short circuiting the electrode voltage.

Contact charging, direct charging or electrodynamic charging exposes a high voltage (15-40 kV) to a semi-conductive spray liquid at the nozzle. As the liquid emerges through a narrow slit, different portions of the liquid obtain the same charge so that they repulse

each other. When the repulsive forces overcome the surface tension, ligaments are formed, which break up into droplets (Matthews, 1989). The 'Electrodyne' pesticide spraying system, and ink spray printing are two applications based on this principle.

Electrostatic techniques can increase spray deposition on plants. When the interception of conventional sprays is low and where the ratio of plant area to ground area is small (Hislop, 1988), increased plant deposits are achieved by reducing deposition on the soil. As crops grow bigger and intercept increasing proportions of conventionally applied sprays, the scope for increasing capture by electrostatic spraying diminishes.

Each electrostatic spraying system has its own limitations. Induction charging systems have the advantage that aqueous sprays can be used so that standard pesticide formulations can be applied. However where a hydraulic nozzle is used, the wide range of droplets emitted do not always result in an improved deposition. Generally, results were better when reduced volumes and smaller droplets were applied. The small droplets, however pose the inherent problem of drift (Matthews, 1989).

Because of its effect on the droplet trajectory, electrostatic spraying was thought to prevent drift. This would make it possible to spray with small droplets. However, these show a high rate of evaporation. This can be prevented by using oil-based formulations. However, many pesticides are unfit to be formulated for non-aqueous solutions.

The electrostatic spray experiments have produced inconsistent results, while there is concern over crop residues and spray drift. Detailed studies of deposits have generally produced large coefficients of variation.

### 3.2.9 Injection

Wastage due to disposal of leftover spray liquid can be reduced to almost zero when direct injection is applied. This technique employs two separate tanks: one for water and one for the concentrated plant protection chemical. The two materials are mixed near the sprayers (Nordby, 1989; Spugnoli and Vieri, 1990).

Injection has the following advantages (Tompkins, *et al.*, 1990):

- environmental protection. Formation of excess spray mixture, which typically is disposed of after spraying with a conventional applicator, is eliminated;
- improved personnel safety. Direct exposure to chemical concentrates, which is most pronounced during weighing, mixing and loading into the tank is greatly reduced;
- the chemical application rate can be changed without changing the nozzle pressure. This means that the optimum drop size spectrum and spray distribution pattern can be chosen.

Some systems use the rotation speed of the pump to determine the flow rate of the concentrated pesticide. Wear of the pump can result in serious errors.

Gebhardt, *et al.* (1984) investigated viscosity and specific mass of the chemicals in relation to the response of the drag-body flowmeter. It appeared that the drag-body flowmeter



must be calibrated for each particular pesticide. Furthermore, it may be necessary to control the temperature of the pesticide to be able to measure the flow accurately.

The place of injection was investigated by Tompkins, *et al.* (1990). The concentration was more constant if the chemical was injected further away from the boom. However the transient time increases and the system responds slower.

Schmidt (1982) developed and tested various direct injection systems. He described a prototype which uses pneumatic equipment for the metering process. The pesticide concentrate is forced in the water line by air. The concentrate flow can be adjusted by varying the pressure difference between the water line and the concentrate tank. They determined an accurate linear relationship between pressure difference and concentrate flow in laboratory tests. Changes in viscosity due to the type of pesticide or to change in temperature can be adjusted with an (electronically operated) controller.

An injection system with a wheel-driven metering pump is described by Reichard and Ladd (1983). A disadvantage of this approach is that the metering pump must be primed by driving a short distance before starting to spray the field. Rapid changes in driving velocity result in errors in the deposition.

Chi, *et al.* (1988) developed a system, in which a metering pump is driven by a DC motor in such way that the pressure drop over the meter is nearly zero (50 Pa). The proper rotary speed of the flowmeter is controlled with a needle valve with a stepping motor. A vane-type fuel pump was used. For fluids with viscosity lower than 90 mPa.s the leakage flow became significant.

Frost (1990) described a metering system in which a metered flow of water is used to control the flow rate of the chemical, making the system independent of the characteristics of the chemical. The metering pump was a gear pump, electrically driven by a 12 V DC motor. Volumetric efficiency depends on rotation speed, viscosity and pressure difference over the metering pump. Specially at low rotation speed (i.e. low flow rates) the inaccuracy is great. A control system was used to compensate errors in flow by changing voltage in relation to the errors in the flow rate. The error over a flow rate of 10 : 1 was found to be less than 5%.

The range of flow rates to provide the full range of dose rates on any conventional machine is at least 120 : 1. This range could be reduced to about 12 : 1 by fitting two units.

Spugnoli and Vieri (1990) described a dosing system composed of a metering pump (dual-chamber hydraulic motor (cylinder)), driven by the clean water flow to the spraying boom. Concentration errors remained within 5% for concentrations ranging from 0.5-3%.

To eliminate the need of a metering pump and the conventional pump, Ghate and Phatak (1991) used compressed air on the pesticide and the water tank. Flowmeters (of type Rotameter) were positioned in water and in concentrated pesticide lines. During the tests the flowmeter was calibrated for each pesticide. Satisfactory results were obtained in laboratory and field tests. Errors were caused by changes in the ground speed.

Three items need special attention:

- precise measurement of the pesticide flow;
- complete mixing of pesticide and clean water. Delay time is an important parameter which should be considered;
- the pesticide pump should be resistant to corrosion by concentrated spraying agents.

### 3.2.10 Computerized dose control

Calibration errors are a major source of inaccuracy in spray application. These errors include deviations from intended driving speed, incorrect orifice size, pressure, and differences due to nozzle wear. The use of spraying computers can affect spraying accuracy in a positive way.

The main goal of spraying computers is to apply the spraying material accurately and equally (Zandbelt, 1990a). A spraying computer can only be helpful when the spraying equipment itself is technically in excellent shape. Spraying computers can be divided into three types of systems:

- information systems;
- information and warning systems;
- information and control systems.

With the first and second type of systems the driver takes all decisive actions, only in the last case the computer can affect the spraying process.

Rice, et al. (1989) concluded that an electronic control system based on radar or fifth wheel forward speed measurement, a turbine flow-meter for boom output measurement and a motorized control valve in the return line to the tank can improve spraying accuracy.

The accuracy of the computer controlled spraying process depends strongly on the accuracy of the various sensors. For instance, driving speed obtained from the rotation speed of one of the wheels can be inaccurate because of the variable slip between the wheel and the uneven ground (Zandbelt, 1990b). An additional fifth wheel gives less slip errors. Radar systems for measuring driving speed however are inaccurate when used in a waving crop or on fields which contain puddles (Zandbelt, 1990c).

# 4 Drop formation

Drops can be produced with different atomizers. How the various atomizers produce droplets is reviewed in the following section. This is followed by an overview of the aspects relating to drop size, such as terminology, crop protection efficiency and the factors which have an influence on the drop sizes.

## 4.1 Atomizers

Atomizers used for agricultural purposes can be divided into several categories:

- pressure-swirl atomizers;
- flat fan atomizers, including deflector nozzles;
- air-liquid atomizers;
- rotary atomizers.

Noteworthy are the many attempts to develop uniform droplet generators. Those which use a controlled frequency pulse either at or above a small hole produce a fairly uniform droplet but do not do so in sufficient numbers; they are subject to frequent clogging.

The discussion below is limited to:

- the atomizers which employ hydraulic pressure to create droplets (the pressure-swirl and flat fan atomizers);
- the atomizers which use both hydraulic and air pressure (air-liquid atomizers);
- atomizers which employ centrifugal forces to create droplets (rotary atomizers).

### 4.1.1 Pressure atomizers

With pressure atomizers (or hydraulic nozzles) the liquid is forced through a small hole causing the liquid film to disintegrate. The drop formation process (under normal spraying pressure) follows four stages (Schmidt, 1980):

- first stage: a neat liquid sheet without any disturbances leaves the nozzle outlet;
- second stage: small wave-like disturbances grow very fast, enhanced by the relative air flow across the liquid surface;
- third stage: the large wave-like disturbances give rise to disruption of the sheet into a maze of thin liquid threads (or ligaments);
- fourth stage: the maze of liquid threads breaks up into separate drops of various sizes, due to further disruptive forces onto the liquid threads.

The physical extent of these stages depends on nozzle geometry and liquid velocity at the outlet, as well as on liquid properties such as surface tension, density and viscosity.

#### *Pressure-swirl atomizers*

Pressure-swirl atomizers have one or more swirl chambers, in which the liquid is given a

rotational speed. The liquid emerges from the nozzle as a thin conical sheet that rapidly attenuates as it spreads radially outward, finally disintegrating into ligaments and then into drops (Lefebvre, 1989). Because of the shape of its spray cloud the atomizer is denoted as a hollow cone nozzle. An additional central hole in the swirl plate fills the cone, in which case the atomizer is denoted as a solid cone nozzle. This type of nozzle generally produces a finer spray than the flat fan nozzle. Their uneven deposit pattern makes it difficult to achieve a uniform overall deposit when fitted to boom sprayers (Southcombe and Seaman, 1990).

#### *Flat fan nozzles*

Flat fan nozzles are pressure nozzles with an elliptical hole. The liquid emerges as a flat liquid sheet, disintegrating into ligaments and finally into drops. The spraying pattern is more or less elliptical. Flat fan sprays are usually rather coarse.

#### *Deflector nozzles*

These nozzles produce a sheet from the impact of a stream of liquid onto a flat surface. They operate at lower pressures and produce a 'coarse' spray with a rather uneven deposit pattern. Other terms for this type of nozzle is anvil nozzle or impact nozzle (Southcombe and Seaman, 1990).

#### *Miscellaneous pressure atomizers*

Ahmad, *et al.* (1981) developed a variable-rate pesticide application system with manifolded bypass nozzles. The bypass nozzle was of the centrifugal pressure type with two swirl chambers. The spray distribution was only slightly affected by a nozzle output flow turn-down ratio of 6 to 1. They concluded that the number of nozzles that can be connected to a single manifold and still meet the uniform pressure distribution criteria is limited and depends on the flow rate. The spray angle varied from 86° to 80° over the 6 to 1 turn-down ratio, while the combined-nozzle spray distribution was only affected slightly.

#### *4.1.2 Air-liquid atomizers*

An air stream can be used to improve atomization quality or to increase the range of the flow rate of the nozzle (Lefebvre, 1989). Usually a high velocity air flow impinges on a relatively slow moving liquid flow. Especially at low liquid pressures atomization is improved using air-assistance. This results in an increase of the liquid flow rate range.

Two different types of air-assisted (or twin-fluid) nozzles can be distinguished (Lefebvre, 1989):

- 1) Internally mixing nozzles with the following characteristics:
  - the mixing of air and liquid occurs just before atomization takes place;
  - the spray cone angle is minimum for maximum airflow and is generally limited to about 60°;

- very suitable for highly viscous liquids;
- good atomization down to very low liquid flow rates.

2) Externally mixing nozzles with the following characteristics:

- the mixing of air and liquid occurs just outside the nozzle tip in the atomization area;
- a constant spray angle at all liquid flow rates;
- no danger of liquid entering the air outlet;
- less efficient with power than internally mixing nozzles.

Air-assisted nozzles need an external supply of high-pressure air.

Cowell and Lavers (1987) investigated two prototype twin-fluid nozzles, designed to apply very low volume rates (0.03-0.18 l/min) and higher volume rates (0.15-0.725 l/min) respectively. They concluded that twin-fluid nozzles have the following advantages:

- even at low application rates (<100 l/ha) the nozzle is less likely to clog than conventional nozzles;
- liquid flow rate and droplet spectrum can be controlled by small changes in air and liquid pressures;
- atomization occurs at relatively low liquid and air pressures.

The main disadvantage is:

- deposit variation across a sprayer boom is highly dependent on the combination of air and liquid pressure.

Cooke and Hislop (1987) also mentioned the advantage of a relatively low application rate together with the absence of nozzle blockage. The balancing of air and liquid pressure may be difficult and poor adjustment may lead to enhanced drift.

According to Brouwer and Weststeijn-Alons (1991) the air flow of twin-fluid nozzles controls drop size distribution and enhances drop velocity considerably at the nozzle outlet.

The wedge-shaped 'Danfoil' atomizers can be considered as a special type of air-liquid nozzles. In these atomizers the air flow is lead across a wedge, where the spraying liquid is dragged out and atomized. The air also serves to direct the droplets to the target area (Brouwer and Weststeijn-Alons, 1991).

#### 4.1.3 Rotary atomizers and CDA

Rotary atomizers are used with the so-called CDA (Controlled Droplet Application) technique. CDA uses centrifugal energy to break up the spray fluid into droplets. Liquid is fed near the center of a spinning disc or conical cup, whose plane of rotation may be horizontal as well as vertical. The liquid is forced by centrifugal forces to the edge of the spinning surface and thrown off either as single droplets or, with higher flow rates, as ligaments. The ligaments usually break into two droplet sizes the main droplets and smaller satellites. If the flow is too high, sheets of liquid leave the spinning disk and break up at random in a similar manner to the action of a hydraulic nozzle. Control of both flow rate and disc speed is essential to ensure that the size of the droplets is correct. The discs or cups are referred to as rotary atomizers.

Bals (1969) investigated the design of rotary atomizers. He concluded that filament atomization produces smaller droplets than atomization based on single droplets coming of the rotary element. The filament formation was achieved by fine teeth on the rotating disc.

Boize and Dombrowski (1976) described tests with an atomizer, consisting of two stacked, ridged discs, placed under 45°. It was found that at low flow rates drops were produced directly from the peripheries of the double disc assembly giving rise to an effective monodisperse spray. For all other flow rates liquid is discharged in the form of ligaments which break down into a wide spectrum of drop sizes.

Nation (1982) mentioned a form in which the spinning disc rotates in the vertical plane, all upward moving drops being collected and recycled, so that the delivery is in the form of a downward flat fan ('Girojet'). Only the mechanism of drop formation is the same as for the other CDA systems. The behavior of the drops will be different from those produced by horizontal discs because of their high initial downwards velocity.

Rotary atomizers produce a fairly narrow droplet spectrum if speed and flow rate are controlled properly. The use of a large cone shaped cup with deep groves ending in a needle point makes it possible to produce uniform drops at low flow rates. The 'Micromax' rotary atomizer is based on this principle. If this atomizer is used properly under the right conditions good weed control can be obtained (Bode and Butler, 1983). The drop size can vary from 300 µm for drift free herbicide application to 20 µm for efficient mosquito control (Bals, 1975).

Equipment with spinning discs allows the use of spray volumes in the range of 10-60 l/ha so that less time is lost refilling the sprayer, and more time is used for actually spraying. CDA has been found to be particularly useful with open targets such as with the application of pre-emergence herbicides to soil. Problems have been signalled with the penetration of dense crops (Southcombe and Seaman, 1990).

## **4.2 Spray angle of the atomizer and atomizer placement**

### *Spray angle*

The spray angle of a nozzle is the angle with which the spray liquid exits the orifice. Spray angles are determined at a pressure of 300 kPa. The spray angle of most nozzles decreases at lower pressures. Cone nozzles have a standard spray angle of 60° or 90°, while flat spray nozzles are produced with spray angles of 45° to 150°. Flat spray nozzles with 110° are standard in Europe according to Nordby (1989).

Underleaf applications and strip applications can be performed better with nozzles with large spray angles.

The 'Girojet' atomizer (a vertically mounted rotary type atomizer) has a spray angle of 140°. This makes it possible to mount the atomizers with a distance of 1.5 m on the boom (Tecnomat, 1991).

A larger spray angle gives the possibility to keep the spray boom lower over the crop so

that drift and swinging of the boom is reduced. This requires more attention to the balancing of the boom.

### *Atomizer placement*

Field sprayers are typically equipped with 110° flat fan nozzles spaced at a distance of 0.5 m giving an operating height in the order of 350 mm above the target surface (Miller, 1991). Flat fan nozzles are commonly mounted with an angle of 5° in the driving direction, so that the individual nozzles spray somewhat behind each other and overlap two to three times. In some cases changing this angle to 20° improves spray distribution over the crop (Porskamp, 1986, 1988).

The spray distribution pattern from air-assisted field sprayers is different from conventional sprayers if the nozzle is placed inside the air flow (see § 3.2.6).

Nozzles on such sprayers should be placed at closer intervals on the booms as compared to conventional intervals. On the 'Degania' sprayer the distance between the nozzles is 25 cm, in contrast to the conventional distance of 50 cm (Hadar, 1991).

Bode and Butler (1983) concluded that for 'Micromax' rotary atomizers spacings of 100 to 120 cm result in much better spray patterns than the wider 200 to 220 cm spacings.

Tecnomax (1991) recommends for the 'Girojet' atomizers a spacing of 1.5 m and a spraying height of 75 cm. A coefficient of variation of 12% is mentioned. Variation coefficients of less than 12 and 9 indicate a sufficiently regular and a good spray, respectively (Porskamp, 1986).

### **4.3 Drop size, drop size spectrum and drop velocity**

Many researchers have shown that smaller droplets are more effective in control of insects, mites and fungi. Smaller drops have also been shown to be prone to emissions to the air and to evaporate more rapidly (see also § 6). This is not surprising, since the total number of drops, the total surface area of the drops and the total area which is covered increases exponentially when the drop size is decreased. When the drop size is halved, a given volume will contain 8 times the number of drops, while the total surface area is doubled. In other words: when the drop size is halved, halve the spray volume could achieve the same extent of cover. Table 4 shows the relation between the droplet diameter and the droplet frequency. In theory, the necessary pesticide amounts could be considerably reduced when the drop size is decreased. Research is necessary to evaluate the practical applications (MJP-G, 1990).

While small drops are prone to be picked up by air currents, large drops easily run off the leaves. This implies that the spectrum of drop sizes is important. Drift and run-off can be reduced by using atomizers which produce a narrow drop size spectrum (Göhlich and Westphal, 1991). Before discussing the ways in which the drop size and the drop size spectrum can be affected, the terminology which is used in discussing these two topics is reviewed.

Drops are commonly referred to as spheres. However, a drop moving through air tends to flatten fore and aft. The extent to which this happens increases with the Reynolds number and the air velocity relative to the drop, and decreases with increases in surface tension which gives cohesion to the drop (Carlton, et al., 1990).

With pressure atomizers, the velocity of droplets leaving the orifice is proportional to the square root of the liquid pressure (see § 8.1). Initially all drops have the same velocity. However, small drops are very sensitive to the drag forces of the surrounding air (see § 8.2.3). They very quickly acquire the local air velocity. Larger drops can maintain their high initial speed for a while. Additionally, larger drops will have a larger final velocity (if it can be reached during the time available) than the smaller drops.

**Table 4** The influence of drop density on coverage and on distance between drops (from Porskamp, et al., 1985).

Application rate (l/ha)	Drop size (µm)	Drop density (drops/cm <sup>2</sup> )	Coverage (%)	Drop distance (mm)
400	100	7639	60.0	0.11
	200	955	30.0	0.32
	400	119	15.0	0.92
40	100	764	6.0	0.36
	200	96	3.0	1.02
	400	12	1.5	2.89

To keep drift as low as possible, a high initial drop velocity is needed. However, increasing the liquid pressure has only a limited effect on initial drop velocity, due to the square root relationship. Besides, an increase in liquid pressure affects the drop size and drop size spectrum in such a way that even more small drops are formed. Consequently, this may result in increased drift, the opposite of what was to be achieved.

#### 4.3.1 Drop size terminology

Drop sizes are measured in micrometers (also referred to as microns or µm's). In practice spray volumes contain a wide range of droplet sizes, while the distribution of the drop sizes can vary greatly. In the discussion of experiments both the classes of drop sizes and the distribution of the drop sizes need to be mentioned. The following terms and classes are commonly used (Porskamp, 1989):

- Volume Median Diameter (VMD, D50, D<sub>0.5</sub> or D<sub>v,5</sub>): indicates that 50% of the spray volume consists of droplets smaller than the given diameter (see Figure 2).
- Number Median Diameter (NMD or D<sub>N,5</sub>): indicates that 50% of the number of droplets consists of droplets smaller than the given diameter.
- Mass Median Diameter (MMD): indicates that 50% of the total spray mass has a diameter smaller than indicated (Lefebvre, 1989); identical to Volume Median Diameter.
- Sauter Mean Diameter (SMD or D32): indicates the diameter of a droplet whose volume-to-surface ratio is equal to that of the entire spray (Lefebvre, 1989).

The ratio between VMD and NMD is frequently used to express the uniformity of the drop size spectrum. A spray with a small drop size spectrum is characterized by a



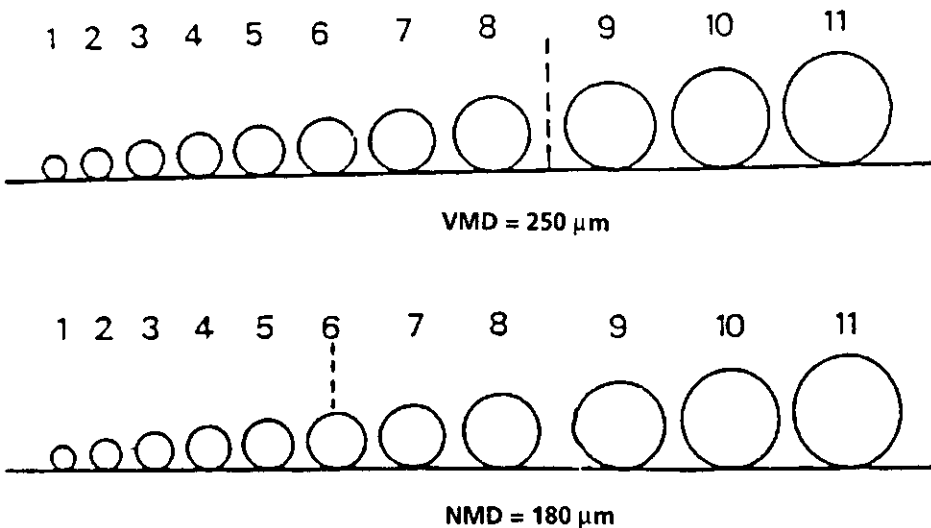
VMD/NMD ratio close to 1. Western, *et al.* (1985) presented ratios for various types of atomizers as shown in Table 5.

**Table 5** VMD/NMD ratios for various types of atomizers (from Western, *et al.*, 1985).

Atomizer type	Pressure (kPa)	VMD/NMD	RS
110015LP	100	5.3	1.4
110015	300	9.5	1.7
8003	300	5.9	1.5
11003	300	7.6	1.6
'Micromax' (3500 rpm)		2.0	0.9
'Micromax' (5000 rpm)		2.1	0.9

Other terms which are frequently used include:

- D10 (or  $D_{v,1}$ ): which indicates that 10% of the volume contains droplets smaller than the given diameter;
- D90 (or  $D_{v,9}$ ): which indicates that 90% of the volume contains droplets smaller than the given diameter;



**Figure 2** Schematic presentations of Volume Median Diameter, VMD, and of Number Median Diameter, NMD.

- Relative Span (or RS): which is defined as

$$RS = \frac{D_{v,9} - D_{v,1}}{D_{v,5}}$$

Common values of RS for various atomizers are given in Table 5. A small value of RS indicates a narrow range of drop sizes.

- Arnold (1983) characterized a spray by volume below a particular droplet diameter, e.g. 100 μm. This is similar to the D10 and D90 concepts, but with variable fractions.

Note that the mean diameter D32 is defined essentially different from the median diameters D10, D50 and D90.

**Table 6** Spray classification based on D50 (from Porskamp, 1989).

Class	D50
Very fine	<150 $\mu\text{m}$
Fine	150 $\mu\text{m}$ - 200 $\mu\text{m}$
Medium	200 $\mu\text{m}$ - 300 $\mu\text{m}$
Coarse	300 $\mu\text{m}$ - 400 $\mu\text{m}$
Very coarse	>400 $\mu\text{m}$

The British Crop Protection Council (BCPC) introduced a system to indicate the type of spray quality or range of droplet sizes for a nozzle. Nozzles are tested to standard protocols and classified into categories of 'Very Fine', 'Fine', 'Medium', 'Coarse' or 'Very Coarse' (Southcombe and Seaman, 1990). Porskamp (1989) modified the protocols for use under Dutch conditions (see Table 6). The 'Fine', 'Medium' and 'Coarse' nozzles are most widely used, while the 'Very Fine' and 'Very Coarse' nozzles are especially used for fogging machines or liquid fertilizers, respectively.

#### 4.3.2 Factors affecting the drop size and the drop size spectrum

Selcan and Göhlich (1982) developed equations with which the drop size spectra could be calculated for flat fan nozzles. They could predict the VMD with an average error of  $\pm 7.5\%$ .

Arnold (1983) measured the size of droplets produced by flat fan nozzles at various locations and heights of the spray fan with a Malvern Particle Size Analyzer. He found that the drop size (VMD) is smaller in the center of the spray fan than at the edge. Absolute numbers on drop size and drop size spectra should be handled with care, since these parameters are very different when they are measured with different instruments (Western and Woodley, 1987; Ripke, 1990) (see also § 7.1).

The size of the drop and the drop size spectrum is determined by

- the type of atomizer;
- the orifice size of the nozzle;
- the condition of the nozzle;
- the spraying pressure;
- the physical properties of the carrier material.

#### *Type of atomizer*

Arnold (1983) measured drop sizes from flat fan nozzles with 110°, 80° and 65° spray angles with constant output. He concluded that a narrower spray angle results in a higher VMD and in a lower percentage of droplets smaller than 100  $\mu\text{m}$  (see also § 4.2). He also found that the percentage of droplets smaller than 100  $\mu\text{m}$  peaks at approximately 20 cm under the nozzle.

The drop sizes created by air-liquid atomizers can be more or less manipulated by varying the air and liquid pressure. Cowell and Lavers (1987) found that the drop size expressed as VMD, decreased linearly with an increase of air pressure (at constant liquid pressure) and with an increase of liquid pressure (at constant air pressure).

#### *Orifice size, spraying pressure and drop size*

Nozzles with smaller orifices produce smaller droplets. Higher spraying pressures also reduce the drop size, but to a much smaller extent. Orifice size and spraying pressure also affect the application rate: smaller orifices and lower spraying pressures both reduce the application rate (Porskamp, 1989).

#### *Condition of the nozzle*

Tilted, worn out, clogged or dirty nozzles produce poor spray distributions and need to be cleaned or replaced.

The choice of nozzle materials affects the rate of wear greatly. Most resistant to wear are ceramic nozzles, followed by stainless steel, and by plastics. Bronze, brass and aluminum are least resistant to wear (MJP-G, 1990).

Air-liquid atomizers would be less susceptible to clogging at volume application rates below 100 l/ha than conventional nozzles (Cowell and Lavers, 1987).

#### *Physical properties and drop size*

Surface tension, viscosity and density are the most important physical properties which affect drop size. They can be manipulated by the addition of oils, emulsifiers, water soluble polymers and other adjuvants and solvents. These additions have been found to alter not just the drop sizes, but also the distribution of the drop size spectrum (Akesson and Yates, 1989).

Arnold (1983) found that increasing the concentrations of the wetting agent Agral 90 (ICI) up to approximately 0.02% v/v has little effect on the droplet-size spectrum of an 80° flat fan nozzle. Further increases up to 1% v/v, decreases the VMD and increases the percentage of spray by volume with droplets smaller than 100 µm. He concluded that a 0.1% concentration (which has been used for most droplet size spectra analyses, and in most sprays in practice) has a slight effect.

Drift retardants aim to limit the number of very small droplets by increasing the viscosity of the spraying liquid. However, many of these additives (such as Vistik, Dacagin and Norbak) shift the droplet spectrum, so that larger droplets and more large droplets are produced. Schmidt (1980) tested additives on the German market which reduce evaporation (Synergid, Sunöl, Bayeröl and AVD). The increased viscosities and reduced surface tensions resulted in a shift towards larger drop sizes. Such a shift towards larger droplets

is undesirable from the points of a good deposit distribution and of a reduction of application volumes.

Schmidt (1980) showed that the drop size spectrum is much less affected by the spraying pressure at lower surface tensions (32.3 mN/m as compared to 72.83 mN/m for distilled water). A lower surface tension at low pressures results in a smaller drop size spectrum, while the drop size spectrum becomes larger at high pressure (250-600 kPa). The same author studied whether tracers which are used in drop analyses affect the physical properties of water. He found that some of these tracers change the surface tension and may affect the drop size (see § 7.2.2 for further details).

#### 4.3.3 Drop size and crop protection efficiency

Biologists have demonstrated highly effective control of insects and fungi with aerosol type applications (<50  $\mu\text{m}$ , and even 0.001  $\mu\text{m}$ ). The physical requirements of generating and delivering these aerosol type applications to target crops and pest habitat generally require larger drops of more predictable movement and deposit characteristics (Akesson and Yates, 1989).

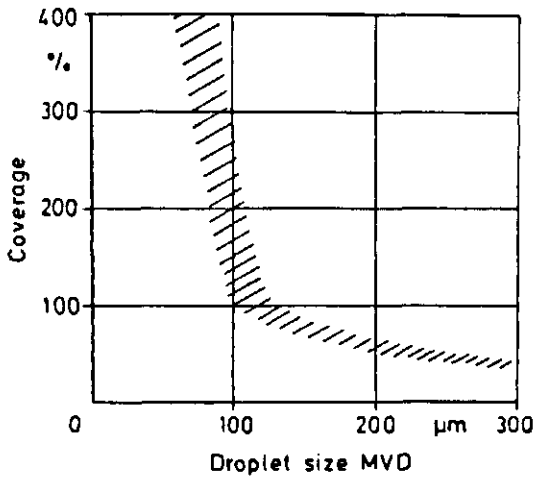
Research on the most effective drop size/spray concentration for weed control in the range of 100-150  $\mu\text{m}$  has not been conclusive, except for glyphosate which is most effective at higher concentrations and at lower volumes (Hislop, 1987). Several authors (Hislop, 1987; Adams, *et al.*, 1987; Hall, 1987) stress that each combination of pest and crop has its own optimum pesticide deposit. The relations between droplet size, concentration of active ingredient and droplet frequency on targets is complex. The problem is enhanced by the fact that translation of laboratory studies to field conditions is difficult and often misleading.

The influence of droplet size becomes even more important when the biological target is on the underside of a leaf. Göhlich (1985) presented a figure which shows that droplets below 100  $\mu\text{m}$  generally provide a better coverage on the undersides of leaves than larger droplets (see Figure 3).

Bailey, *et al.* (1982) described six experiments in which various combinations of drop size and volume of application have been compared with respect to the control of broad leaved weeds. A 'Micromax' CDA sprayer was used. Applications at 40 l/ha were superior to those at 20 l/ha. Variations in drop size resulted in broad-leaved weed control of 71.1, 76.3 and 70.0% for drop sizes 125, 157 and 250 respectively.

Bode and Butler (1983) suggested that a narrow drop size spectrum results in a high coverage. A spray containing only 200  $\mu\text{m}$  drops applied at 10 l/ha would result in a coverage of 24 drops per  $\text{cm}^2$  of soil surface. To obtain equivalent coverage with a much wider droplet spectrum, would require applying many more liters per hectare.

Adams, *et al.* (1987) found that a 3.5 fold decrease in diameter (from 108  $\mu\text{m}$  to 31  $\mu\text{m}$ ) caused a twelve-fold reduction in the required amount of insecticide to obtain 50%



**Figure 3** Dependence of coverage on the undersides of leaves on droplet size (after Göhlich, 1985).

mortality of glass-house whitefly. The required amount of pesticide to obtain a 50% mortality in two-spotted red spider mites was found to decrease from 62 ng/cm<sup>2</sup> to 11 ng/cm<sup>2</sup> when droplet size was reduced from 80 μm to 20 μm.

Crease, et al. (1987) suggested that the extent of leaf coverage determines the probability of pesticide encounter and thus affects the effective dose of pesticides. This would hold especially for contact pesticides. At low drop densities (<20/cm<sup>2</sup>), the area of leaf covered may be directly proportional to the number of drops present. However, as the drop density increases (>20/cm<sup>2</sup>), deposits coalesce or overlap on the leaf surface to result in progressively smaller increases in leaf coverage.

Omar and Matthews (1987) studied the effect of varying the drop size and concentration of permethrin on the knockdown and mortality of the mobile diamondback moth *Plutella xylostella* (L) on brussels sprouts. They concluded that in order to achieve a similar mortality, the increase in droplet number required when halving the droplet diameter was estimated at only fourfold instead of theoretically eightfold.

Pest control was found to be more effective for drops of 140 μm than of 300 μm. While the volume of the toxicant deposited may be the same, a better coverage is realized with smaller drops (Akesson and Yates, 1989).

A contact pesticide requires a better drop coverage than a systemic pesticide. A better drop coverage usually coincides with smaller droplets and therefore more drift. Most herbicides are systemic substances and can be applied in large droplets, while most insecticides and fungicides are contact substances which need to be distributed in small droplets. Akesson and Yates (1989) quoted research which showed that the increase in effectiveness as a result of a decrease in drop size (665, 465, 335 and 155 μm were tested) was greater for contact type herbicides than for systemic herbicides.

# 5 Deposition

The performance of crop protection equipment cannot only be evaluated from an environmental point of view; the biological effectiveness, and thus the distribution and deposition of the active ingredient, must also be examined. An improvement in the design of the equipment, which for instance results in reduction of drift, is only worthwhile as long as the active ingredient reaches its intended target. This makes co-operation between agricultural engineers, specialists in plant protection and plant scientists in the development of new equipment desirable (Göhlich, *et al.*, 1979).

When a drop of a liquid impinges on a solid surface (e.g. a leaf)

- it may bounce or undergo fragmentation into two or more smaller droplets which in turn may bounce back and return to the surface with a lower kinetic energy;
- it may adhere to the surface after passing through several stages whereby it flattens, retracts, spreads and finally rests to form a hemispherical cap;
- or it may float as an individual drop for a fraction of a second or even several seconds after which it can adhere to the surface or leave it again.

(Tadros, 1987).

How droplets penetrate crops, how they impact and adhere to surfaces, and how they are retained by, how they wet and how they spread over surfaces, is described in the underlying paragraphs. How complete sprays are distributed over and in crops and how sprayer booms behave is discussed in the last two paragraphs of this section.

Studies on interactions between spray droplets and plants usually require controlled conditions. Hislop (1987) points out that leaf surface and surface homogeneity, leaf size, shape and orientation of plants grown in 'artificial' environments often differ from those grown under natural conditions. This problem can be overcome by growing the plants outdoor in trays and spraying them under controlled conditions.

## 5.1 Crop penetration

The extent to which spray droplets penetrate a crop is greatly affected by the type of crop. A spray liquid will easily penetrate an open crop with vertical leaf orientations. Research on a potato crop and on various growth stages of cereal crops has shown that different application volumes and drop spectra produced by hydraulic nozzles result in very similar distributions of the spray over different parts of the crop: most of the spray is deposited on the upper third of the canopy. Crop density however has an important impact on the range of deposits and eventual through-fall to the underlying ground (Hislop, 1987). Ground deposits in a mature cereal crop amount generally to some 15%.

Akesson and Yates (1989) suggest that larger drops, travelling at greater velocities could be helpful in penetrating brush canopy and with shattering produce a significant increase in coverage through generation of many small drops. This might be enhanced by the use of surfactants which reduce the rebounding of drops and promote the break-up

of large drops striking leaves, twigs and needles. Several authors have found smaller drops in the inner regions of a crop canopies than in the outer regions (Afreh-Nuamah and Matthews, 1987). This agrees with the theory described by Carlton, *et al.* (1990) that smaller airborne particles behave like the air molecules in which they are transported: when they encounter an obstacle, they readily change their path and move around it. Larger spray particles have a greater chance of impaction because they have more momentum and require more time and distance to slow down, change their paths, and move around an obstruction than do the air molecules.

Jepson, *et al.* (1987) studied penetration of droplets of various sizes in a wheat crop. They found that mean drop size (both VMD and NMD) showed trends to increase through the canopy, although some of the smallest droplets penetrate to all levels. They suggested that the increase in the number of 100-200  $\mu\text{m}$  droplets was a result of the shattering of large droplets, followed by a collision with the canopy. This seems to contradict with Göhlich (1985) who presented a figure showing a decrease in drop size (VMD) with increased penetration depth in plant canopies such as cereals or maize. He suggested that the larger droplets settle mainly at the upper part of a plant structure. This effect is even more pronounced when air-assistance is applied.

Taylor and Anderson (1987) studied the effect of 1) application rate (100, 200 and 300 l/ha) 2) drop size (fine, medium and coarse) and 3) growth stage on crop penetration in winter wheat. Growth stage of the wheat had a major effect on how much spray reached the ground. Cereals were extremely efficient in retaining the spray, even when this was applied as coarse drops. The spray only penetrated where the cereal canopy was not complete. Application rate and drop size were found to have little effect.

Afreh-Nuamah and Matthews (1987) found that spray penetration of 4 m high apple trees was greater at bud-burst than at full canopy and that more spray was deposited at the bottom than at the upper part of the tree canopy. Use of a charged spinning disc resulted in higher deposits.

Ringel and Andersen (1991) concluded that the extent of spray penetration in a wheat crop can be manipulated by varying the air velocity with air-assistance. The air currents in the crop can cause an increased deposition. They also studied the effect of varying the air direction at constant spray angle and found the highest deposition levels at air angles of 20° forward at maximum air velocities.

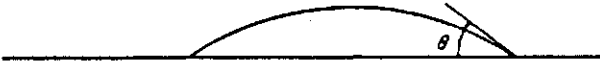
## **5.2 Impaction and adhesion**

Tadros (1987) described the theoretical background of impaction, adhesion, retention and wetting of spray droplets. Parts of his paper are summarized below. The interested reader may find the underlying equations in the original paper.

Droplets with diameters of 20-50  $\mu\text{m}$  have a low momentum and usually reach the leaf surface only if they travel in the direction of the air stream (see also § 5.1). If they do reach the leaf surface, they usually adhere to it. Droplets in the range of 100-400  $\mu\text{m}$ , which are produced by most common spray nozzles, may be reflected or retained depen-

ding on parameters such as the surface tension of the spray solution, the surface roughness of the leaf and the elasticity of the drop surface.

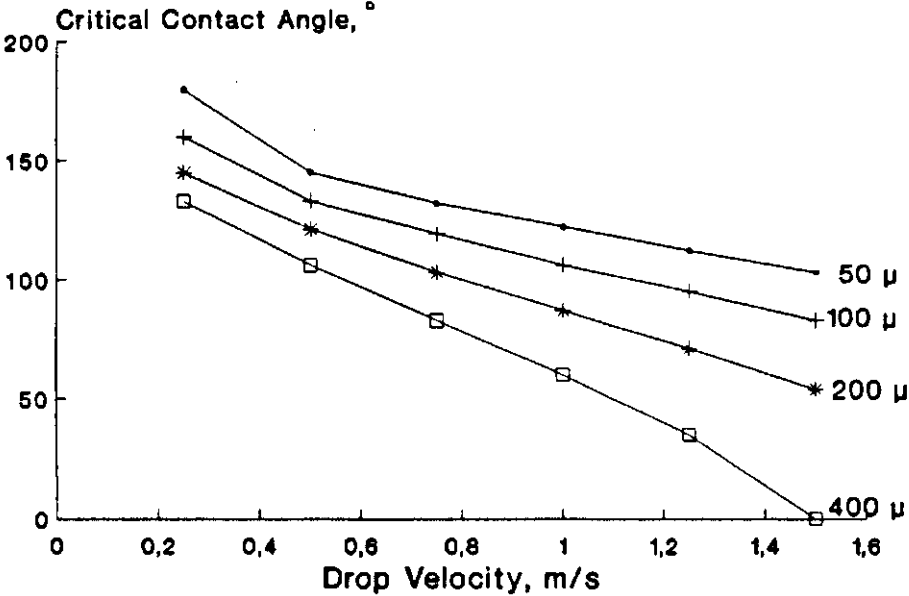
When a water drop is placed on a leaf surface, it takes the form of a spherical cap. This cap is characterized by the contact angle,  $\theta$  (see Figure 4). The smaller the contact angle, the better the liquid is said to wet the solid. Complete wetting means that the contact angle is zero, while complete non-wetting occurs at an angle of  $180^\circ$ . Contact angles of  $180^\circ$  are impossible for a droplet resting on a solid surface. Measurements of contact angle are complicated, since the angle usually exhibits hysteresis.



**Figure 4** Schematic representation of a drop on a leaf surface, and its contact angle,  $\theta$ .

A droplet can adhere to a smooth surface if the difference in surface energy between free and attached drop exceeds the kinetic energy of the drop. The surface energy of a free drop can be computed from its size and its liquid/air surface tension. The surface energy of an attached drop can be calculated based on the areas of air/liquid interface, that of the solid/liquid interface, that of the solid/air interface areas and the accompanying interfacial tensions. Tadros (1987) showed how these are related to the contact angle of the adhered drop. From his example the critical contact angle was computed for a water droplet of a certain size and velocity to adhere to a smooth surface (see Figure 5). No adhesion of these droplets will occur if they have larger contact angles.

From Figure 5 it can be read that the critical contact angle at which drops adhere to a surface decreases when the drop velocity increases or when the drop size increases.



**Figure 5** Contact angle below which adhesion of water droplets of various sizes and velocities occurs on a smooth surface (calculated from Tadros, 1987).



Under practical conditions adhesion may occur at smaller or larger contact angles, since leaves have 'rough' surfaces, with hairs and wax crystals. Experiments on droplet adhesion, however support the data in the figure.

As mentioned above, the calculations were performed for water droplets. Water has a high surface tension (72 mN/m) which implies that water drops have relatively large contact angles. The addition of surfactants reduces the surface tension. A drop with a certain size and velocity will have a smaller contact angle, and will adhere easier when a surfactant is added.

Other authors presented results which agree with the above theory. Young, *et al.* (1987) found that 336  $\mu\text{m}$  droplets travelling at 0.7 m/s bounce and do not adhere to horizontal wheat leaves at their first impaction. Use of adjuvants increased adhesion by reducing the surface tension. Inclining the leaves at 45° and 75° decreased adhesion. Drops of the mentioned size and speed adhered for 100% to the wheat leaves at any orientation, when these had been stripped of their crystalline wax. Matzen and Jørgensen (1990) found that droplets larger than 400  $\mu\text{m}$  and with a velocity higher than 8 m/s often break by impact, and then form low energy droplets which are deposited during the next meeting with the plant. Akesson and Yates (1989) report that large drops (>500  $\mu\text{m}$ ) shatter on impact, while smaller drops (<200  $\mu\text{m}$ ) are less prone to shatter and tend to cling to leaf hairs without reaching the active leaf surface.

### 5.3 Retention, wetting and spreading

The shape of a drop can be influenced by the carrier material and by the leaf surface. Waxy leaves have a hydrophobic surface on which drops have a tendency to retain a spheroid shape. Addition of surfactants to the spray solution will promote spreading of the drops on the leaf surface, while they can also solubilize the wax on the leaf surface (Tadros, 1987).

Once a drop adheres to a leaf it may stay there, but it may also run off. The tilt of the leaf, the drop size, the velocity of impacting drops and the contact angle at the leaf/droplet/air interface and wind speed determine whether the droplets are retained on a leaf. Usually retention increases with reduction of droplet size, but is significantly lower at high droplet velocities and wind speeds. Equations which describe the relations between run-off, the shape of the droplets, the surface tension of the air/liquid interface, the density of the liquid, the tilt angle of the leaf can be found in the paper by Tadros (1987). The author indicates that these equations have limited value, since the surface roughness and presence of hairs are not taken into account, while they play a significant role in retaining droplets. These properties make theoretical approaches extremely difficult.

Anderson, *et al.* (1987) used the contact angle of water as a guide to surface roughness, a smooth non-crystalline paraffinic wax surface giving an angle of 105-110° whereas a rough wax-covered leaf surface can give an angle of 140° or more. They concluded that retention and spreading properties of agrochemical sprays are primarily related to dynamic and equilibrium surface tension, respectively, which implies that they can be altered independently.

Wetting increases the contact area between the droplet and the target. This increases the effect of the pesticide. Many leaf surfaces represent the most unwettable of known surfaces. This is a result of their hydrophobic nature, which gives the leaf surface a 'microroughness'. Tadros (1987) shows that this surface roughness may enhance or reduce wetting. Here again we see a relation with the contact angle, where a lower contact angle increases the wetting and spreading of liquids on leaf surfaces. Reduction of the contact angle can be achieved by the addition of surfactants which adsorb at various interfaces and modify the local interfacial tension.

Many surfactants have been developed with different properties. They are available with anionic, cationic or non-ionic natures, and with different levels of wettability. Some surfactants promote solubilization of the pesticide. Surfactants may be phytotoxic, by type or by concentration. This means that surfactants need to be selected with care. Use of non-ionic surfactants is preferred, since they are compatible with pesticide formulations, while they can also be incorporated in oil formulations (see also § 2.2).

#### **5.4 Distribution over the crop**

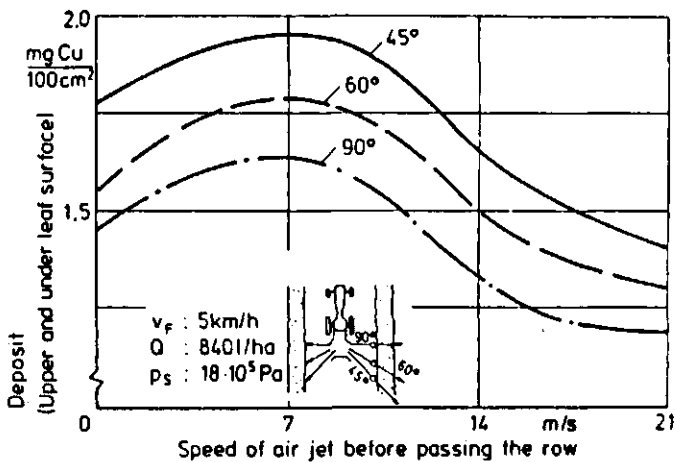
The distribution of air-assisted sprays over tree canopies is affected by many factors such as spray volume, tree size and development stage, and application method. Large volume sprays are better captured at the skirt of the tree (close to the machine outlet) than at their top (Hislop, 1987).

Göhlich (1985) varied the orientation and the terminal velocity of the air flow for blower sprayers in vineyards. He obtained the best deposits of the sprays when the air stream was directed 45° backwards and when the velocity of the air at the edge of the plant row was 6-8 m/s (see Figure 5).

Different volume rates with a constant content (and thus varying concentrations) of Cu as a tracer element were applied with an air-blast sprayer to orange trees. Mean Cu deposit increased as spray volume decreased: 2.27 times more Cu was deposited when the volume was decreased from 9,400 to 470 l/ha. Cu deposit higher in the tree was highest, and in lower parts lowest. Deposition was lowest in the center of the trees, and higher at the 90° azimuth than at the 45° and 0° (Salyani and McCoy, 1990).

Cross (1991) tested the distribution patterns from an axial fan air-blast sprayer in a modern apple orchard with tree heights of 2 m. He concluded that axial fan air-assisted sprayers are poorly suited to modern intensive orchards, since the three types of nozzles which were tested generated large amounts of spray at heights greater than 2 m.

Cowell, et al. (1988) found that a hollow cone nozzle and a spinning disc on a 'Hardi Maxi SPV' sprayer produced similar amounts of deposits on the ground and in the trees in apple orchards. They sprayed with the low application rates of 132 and 88 l/ha for both types of nozzles. Close to the sprayer the deposit on the under leaf surface was greater than that on the upper leaf surface for the hollow cone nozzle. However, similar deposits on upper and lower leaf surfaces were observed close to the sprayer, after spraying with the spinning discs.



**Figure 6** Effectiveness of air jet speed and orientation on chemical deposition in grape vines (after Göhlich, 1985).

Vertical distribution patterns for air-assisted sprayers in orchards can be optimized through choice of orifice size and nozzle orientation at each nozzle position. Nozzle arrangement tables were derived for a crop specific adaptation of the sprayer's vertical distribution pattern. These tables are meant for use by individual farmers (Kümmel, et al., 1991).

Crop sprayers deposit 40-75% of the spray on the target. When fruit trees are treated with a mist spray before they break into leaf, 10-20% of the mist is deposited on the trees, while this percentage increases to 25-60% when the leaves are fully grown (Nordby, 1989).

Deposition patterns may be modified by electrostatically charging the spray drops (see § 3.2.8). Increased deposition as a result of charging is most likely when the capture efficiency of the crop is small (Hislop, 1987).

## 5.5 Influence of sprayer boom movements

Thomas and Göhlich (1986) developed a prototype field sprayer, with an active height and angle analog control system (related to the roll movement). Two ultrasonic sensors based on delay time, measured the position of the sprayer boom. Compared with an uncontrolled sprayer, the deviation of the desired position, measured on the halve width, was on the average 63% less. Based on the measured momentary position a computer program for the theoretical spray distribution was developed.

Frost and O'Sullivan (1986) developed a mathematical model for the NIAE universal twin link boom suspension for roll and yaw movement. Experimental work was carried out to verify the model for a range of suspension geometries. The results showed a good agreement between predicted and measured performance of the suspension in both roll and yaw. Elastic deformation was not considered.

Baltussen (1986) used a CSMP computer model to study the dynamic roll movement of a boom with a trapezoid suspension. A control system to adjust the roll angle during tractor movements was also regarded.

Nation (1987a; 1987b) developed a suspension comprising horizontal and vertical pivots through the center of gravity. With this pair of mutually perpendicular pivots the boom was restrained in both planes by tension springs, combined with viscous dampers. Measurements showed a more effective reduction of transmission to the boom of the roll and yaw movements of the sprayer frame than both a commercial, vertically sprung suspension and a simple, experimental, pendulum arrangement. An analysis was made of the dynamics of this suspension and a computer model developed, based on power spectral densities. Optimum values of damping were computed for ranges of natural frequencies. The model illustrated the importance of a high value of polar moment of inertia.

Porskamp (1988) measured spray distribution under laboratory conditions for flat fan nozzles depending on the angle between each nozzle. Also a computer program was developed to compute the distribution during boom movements in both horizontal and vertical direction regarding one nozzle. He concluded that yaw movements more severely affect deposition than roll movements.

Chaplin and Wu (1989) developed a dynamic computer model, which simulated the movement of a sprayer boom in two dimensions. They investigated also the influence of tank water volume, water slosh and tire inflation pressure on the dynamic behavior of the boom. The water tank was placed perpendicular to the running speed. The model was validated, the motion of the boom tips were filmed.

Mawer and Miller (1989) used a computer model of the spray volume distribution below an 18 m spray boom to study the effects on the spray pattern from individual nozzles and boom roll angle on the uniformity of application. Effect of uniformity is shown to be a function of changes in height of each separate nozzle rather than the small changes in the roll angle.

Houmy and Destain (1990) developed a dynamic model of sprayer boom displacements, based on finite element analysis. The fundamental frequency of a sprayer boom fixed to the frame is 2 Hz, which is close to the excitation frequencies that come from the tractor. The sprayer boom showed a strong coupling, i.e. a vertical displacement imposed on the boom, lead to a horizontal displacement.

## 6 Drift

In pesticide spraying the term drift is commonly used to refer to: the transport of crop protection materials through air movements to the direct surroundings of the treated plot. Drift can occur in the shape of droplets, dust, granulates or vapors. The above definition implies that drift refers to both emission to the air, and to the indirect emission to the soil. Maas and Krasel (1988) make a distinction between direct and indirect drift. They refer to direct drift when the drops never reach the target, but instead are transported during the time of application outside the treated area by wind and/or thermic air currents, where they are deposited or evaporate. They refer to indirect drift as to the active ingredient which is lost by evaporation after the duration of the application. Göhlich, et al. (1979) pointed out that deposition and drift are directly related: the active ingredient which is not deposited on the target is lost as drift.

In order to compare drift levels under various conditions, Young (1991) defined the 'drift potential' (DP) as 'that proportion of the spray output from the nozzle that fails to be deposited within a defined plan area at a standard distance below the nozzle in an air flow of a defined speed.' It should be noted that this does not imply that all material contained in the Drift Potential will actually contribute to drift, but it may do so under the worst circumstances.

The disadvantages of drift are of different kinds (Hartley and Graham-Bryce, 1980):

- 1) the direct loss from the target area may decrease efficacy and waste chemicals and therefore money;
- 2) costly damage may be done to vulnerable crops exposed to the drifting chemical;
- 3) (long-distance) drift may contribute to general environmental contamination;
- 4) possible danger exists for the user.

Measurements have shown that up to 10% of the applied spray dose may be air-borne at a distance 5 m from the edge of the treated area when using arable boom type sprayers. These levels are much higher with air-blast orchard machines (Miller, 1991).

Like others, Walklate (1991) note that the air-assisted sprayers which were developed for the traditional orchards with large bush and standard trees are still being used in the modern orchards with dwarf trees planted at high density. The forced air flow and the spray distribution patterns have not been adapted to the smaller trees, so that excessive drift occurs. He developed a computer model with which he simulated various possible ways of reducing drift. He concluded that the height of the spray distribution near the source, the evaporation rate, the initial spray droplet size and the shape of the spray droplet size distribution can all have a significant influence on pesticide drift from orchard sprayers.

Bäcker and Rühling (1991) found that drift from recycling systems in orchard sprayers was only a fraction from drift created by conventional orchard sprayers. This concerned both the drift at various heights and at various distances (see also § 3.2.7).

Porskamp and Beerens (1991) also mentioned a considerable reduction of drift using the CLS tunnel sprayer in orchards with respect to conventional orchard sprayers, while the rate of deposit on the tree foliage was increased.

Emission by vapor has been estimated to amount to 1-5% for arable crops and 10-20% for high growing crops such as in orchards (MJP-G, 1990). Numbers for separate sectors are presented in Table 7.

**Table 7** Estimated emission by vapor drift (from MJP-G, 1990).

Sector	Total consumption, Tons/year of active ingredient	Emission as vapor, %	Estimated total emission, Tons of active ingredient
Arable crops	4460	1-5	45-223
Vegetables, unprotected	392	1-5	4-20
Flower bulbs	981	1-5	10-49
Stock breeding	705	1-5	7-35
Public parks	140	1-5	1-7
Fruit production	373	10-20	37-75
Tree production	154	10-20	15-31
<b>Total</b>			<b>118-440</b>

## 6.1 Application conditions and drift

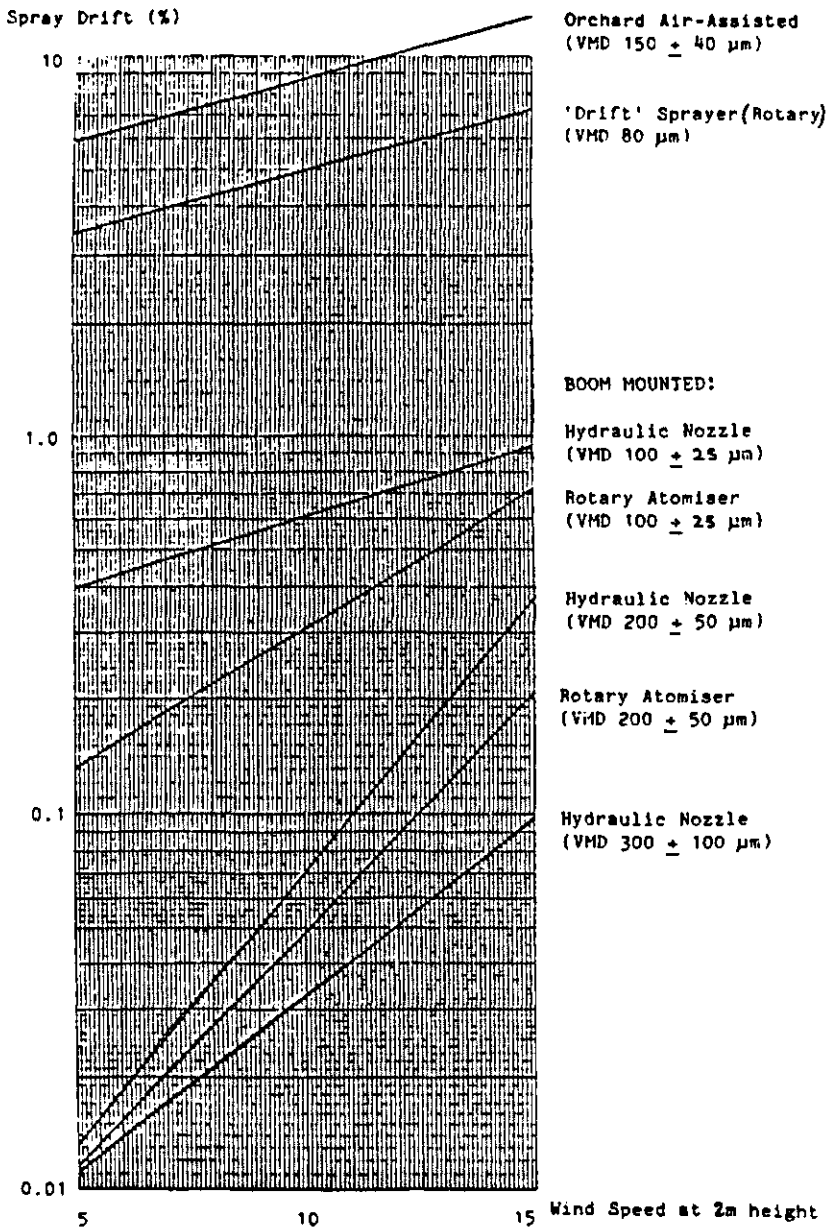
Drift is a function of the atmospheric conditions into which the spray is released. These conditions are difficult to define. Therefore, field measurements examining the performance of a given spraying system commonly use comparative techniques (Miller, 1988). Wind speed, temperature and relative humidity, and crop morphology are reviewed with respect to drift in the following sections.

### 6.1.1 Wind speed and drift

Wind is the major climatic factor which affects drift in air-assisted orchard sprayers (Göhlich, *et al.*, 1979). As an example they point out that an increase of the wind speed from 1 m/s to 2 m/s increases drift more than raising the spraying pressure from 800 to 1800 kPa.

Gilbert and Bell (1988) estimated total drift passing a line 8 m downwind from the boundary of a treated area for different types of sprayers and for various wind conditions. The drift estimations were based on many separate trials with different types of sprayers and under a range of wind conditions. Their results were summarized in a graph, which is shown in Figure 7 (see also § 7.3.1).

Western and Hislop (1991) found that spray drift from droplets with a VMD of 129  $\mu\text{m}$  increased linearly with wind speed. Air-assistance greatly reduced drift. This reduction was greater when the air pressure was increased. Adding electrical charge to the air-assistance had a slightly negative effect on the drift reduction.



**Figure 7** Spray drift as percentage of applied spray vs wind speed (from Gilbert and Bell, 1988).

Ringel and Andersen (1991) reported that air-assistance is especially effective at reducing drift under higher wind speed conditions. Drift from air-assisted spraying at a wind speed of 8.5 m/s was similar to that at a wind speed of 3 m/s with conventional spraying. Air-assistance does not reduce drift under wind-still conditions, provided the nozzle fulfills the requirements.

Several authors (Ripke, 1990; Koch, 1989) presented frequency curves of wind speeds over the time of day. These showed that the lowest wind speeds occur during night time.

Göhlich, *et al.* (1979) pointed out that drift reductions of up to 50% can often be achieved by spraying at a different time of the day.

### 6.1.2 *Temperature, relative humidity and drift*

Ripke (1990) quotes research which indicated that small droplets evaporate for a great deal before they reach their intended target. 20 µm droplets lost 41.8% of their volume in the first 35 cm of their flight when sprayed normal to the ground, at a driving speed of 3 km/h, with an operating pressure of 300 kPa and at a relative humidity of 80%. This volume reduction increased to 75.6% at a relative humidity of 60%. In contrast, 500 µm droplets lost only 0.7% at a 40% relative humidity.

Evaporation can occur not only during application from the fluid phase, but also after the droplets are deposited, even from the dry phase. Evaporation after deposition is stimulated when leaf and soil surfaces are warm (Koch, 1989).

During the day the air layer near the ground is unstable. The drift depositions in the neighborhood of the application (0-6 m) are remarkably low at low relative humidities. The drift concentrations usually increase in the outlying surrounding (10-70 m away). The thermic conditions are generally more stable during morning and evening times, which renders these preferred times of application from the point of air stability (Göhlich, *et al.*, 1979).

Inside a spray cloud the relative humidity is independent of the prevailing relative humidity: as a result of the large number of droplets it approaches saturation (Hosseinipour, 1979).

### 6.1.3 *Crop morphology and drift*

The extent of drift has been found to be related to the stage of development of the crop. Ringel and Andersen (1991) found that air-assistance in field crops can reduce drift by 50% when bare ground is sprayed, while this drift reduction reaches 90% when a closed crop is sprayed.

Göhlich, *et al.* (1979) found that drift in apple orchards was often a multiple of that in vineyards. They also found that the apple orchards provided a smaller filter which resulted in deposits in the driving lane and the 3 adjacent lanes which were at least twice as high as in vineyards.

## 6.2 **Application technique and drift**

Besides the parameters which are described in more detail, Miller (1988) mentions trajectory angle and release velocity as parameters which influence drift levels. They both affect droplet flight times and hence the exposure to natural wind effects.



### 6.2.1 Drop size, drop velocity, drop direction and drift

Small droplets are much more prone to drift. Small droplets are lighter in weight and can easily be carried by wind, and in addition are more susceptible to evaporation because they have a much greater surface to volume ratio (see also § 4.3). In general the critical droplet size at which drift just does not occur lays, for most field conditions, between 100 and 150  $\mu\text{m}$ . 100  $\mu\text{m}$  can be used when the wind speed is lower than 3 m/s and the distance over the crop is 45 cm or less. Usually a droplet size of 150  $\mu\text{m}$  is advisable.

Downward direction and increased drop velocity reduce drift: flat fan nozzles direct the droplets more downward than cone nozzles (see also § 4.1). Air-assistance with downward directed air reduce drift (Ringel and Anderson, 1991).

Göhlich, et al. (1979) found that a higher spraying pressure increased the drift from air-assisted orchard spraying. He concluded that the higher pressure reduced the VMD. Smaller droplets have a lower sedimentation velocity and a shorter life time, and are easier picked up and dispersed by the prevailing air currents.

Maas and Krasel (1988) measured drift from different flat fan nozzles and additives when spraying at an application rate of 300 l/ha. They concluded that low pressure nozzles (e.g. LP 11004 or LP 8004) cause less drift than similar conventional nozzles (e.g. 11004 or 8004). Use of a nozzle with a smaller spray angle also caused less drift. This could be a result of the fact that nozzles with a smaller spray angle produce larger drops (Arnold, 1983).

Ripke (1990) found that both emissions to the air and to the soil were larger when the drop size was smaller. The twin-fluid Air Jet TK3 nozzle, the flat fan nozzle 11002 XR and the dual flat fan nozzle DF447-04 created relatively large amounts of drift under the conditions of his experiments.

Hobson, et al. (1990) simulated various conditions in cereals with a computer model. The results indicated that drift occurs primarily with droplets smaller than 100  $\mu\text{m}$ . Orifice size and operating pressure would not influence drift greatly. Spray drift was larger from runs with 80° nozzles at 0.5 m above the crop as compared to runs with 110° nozzles at 0.35 m above the crop. This despite the fact that the 80° nozzle produced a relatively coarse spray quality.

Spray drift from droplets in the 20-100  $\mu\text{m}$  range increased approximately linearly with wind speed. Relative humidity of the local air was not a parameter in the model, with the result that the effect of evaporation on drift enhancement was overestimated. (The literature on effects of temperature and relative humidity on drift is reviewed in 6.1.2).

Miller (1991) developed a computer model to predict drift under various conditions. He found that droplets with a diameter of <75  $\mu\text{m}$  are mainly responsible for drift. Small droplets (<30  $\mu\text{m}$ ) follow the turbulent movements of the air and tend to move around objects. The movement of larger droplets is affected by inertia effects. Evaporation of small drops depends much less on wind speed than that from a large surface of water. The relative velocity of the drop with respect to the surrounding air is severely limited because the drop moves with the wind (Hartley and Graham-Bryce,

1980). These authors showed that the life of air-borne water drops is proportional to the square of their diameters. That implies that the finer drops in an ordinary spray of mixed drop sizes will disappear, while the larger drops are still not much reduced in size. As an example they indicated that at 20°C and 50% relative humidity, a 50 µm diameter drop has a life time of 4 seconds, while during that time a 100 µm drop will have decreased to 87 µm and a 200 µm drop to 193 µm.

### 6.2.2 Boom height, boom orientation and drift

The greater the distance between source and target, the greater the danger of drift. Drift potential can be reduced by working with the smallest possible boom height.

The smallest possible boom height can be achieved with sensor aided boom height alignment, or with aids which reduce swinging of the boom. Göhlich and Westphal (1991) depicted an orchard sprayer which can align the atomizers to a fixed distance from the various parts of the trees.

Göhlich, *et al.* (1979) performed many drift experiments in apple orchards and vineyards with various types of air-assisted sprayers. Upwards sprayed droplets are much more likely to be captured by air currents than droplets which are sprayed in a downward direction, and are more liable to drift. They found that when the fan is installed high, and the spray and air flows are directed mainly downward, the emission to the ground and to the air can be reduced with some 33% and 50%, respectively, compared to the conventional equipment which directs the flow upwards. Downward spraying was not found to increase the emission to the ground as was feared. In vineyards they did find that deposition on the bottom sides of the leaves was considerably reduced when the spray and the air were directed downward, but when the flow angle was shifted from 90° to 45° backwards with respect to the driving direction, this reduction in deposition on the bottom parts of the leaves was almost compensated for.

Miller (1988; 1991) found a 75% increase in air-borne drift when boom height was increased from 0.5 to 0.7 m. These results were obtained from experiments above short grass in a mean wind speed of 5.1 m/s (at 10 m high).

### 6.2.3 Driving speed and drift

Miller (1988) suggested that higher driving speeds increase the effects of air disturbance around the boom and vehicle, and of the horizontal component of droplet velocities. This is likely to influence and probably increase drift. He indicated that further research and development is required to quantify the effects of vehicle and boom movement on the associated air disturbance and the interaction with sprays. This could produce design criteria and data so that further design improvements to be made.

Göhlich, *et al.* (1979) found in experiments on air-assisted orchard spraying that a higher driving speed results in higher emissions to the air and to the ground.

Ringel and Anderson (1991) reported a doubling of drift in wheat experiments when

driving speed was increased from 4 km/h to 10 km/h when no air-assistance was applied. With air-assistance, drift was the same at these two driving speeds.

When the driving speed is higher, the droplets are sprayed over a larger air volume. This increases the evaporation rate with a subsequent reduction in droplet size. In addition, the downward sprayed droplets are increasingly forced backward, away from their vertical flight direction, so that the path to the target is increased in length and in time (Ripke, 1990).

#### *6.2.4 Application rate and drift*

Ringel and Anderson (1991) found a fourfold decrease of drift in wheat experiments when they increased the application rate from 100 l/ha (with a 4110-12 nozzle at 250 kPa) to 200 l/ha. Drift was similar at these two application rates when air-assistance was applied. However, they did not mention by what means the application rate was changed (driving speed, spray pressure, or altered nozzle type).

#### *6.2.5 Air-assistance and drift*

While air-assistance is said to improve penetration and deposition, presently much more attention is paid to the drift reduction capability that has been reported to be achieved by using air-assistance.

#### *Field crops*

Air-assistance provides drift stability without changing the droplet spectrum. According to Ripke (1990) considerable drift reduction could be achieved using air-assistance in crop spraying. Ringel and Anderson (1991) studied the effect of air release angle (20° forward, vertical and 30° backwards), and of airspeed (0, 16 and 28 m/s) on emission to the air and to the ground and depositions in winter wheat using a 'Hardi Twin' sprayer. They found that emissions to the air and to the ground were most effectively reduced when the air was released with a forward angle of 20° at the highest airspeeds. Crop depositions were highest under these circumstances. This was supported by the experiments of May (1991), who reported that a rearward angled sprayer boom resulted in more drift than in the vertical case.

Watson and Wolff (1985) found that spray deposition both on the entire plant and on the upper-plant bottom leaf surfaces could be improved using a shroud of air around each spray nozzle. Both flat fan and hollow cone nozzles, mounted on a vertical boom in between the rows, were tested in spraying corn and soybean plants.

Western and Hislop (1991) tested an experimental air-assisted sprayer in a wind tunnel study. At all levels of air-assistance spray drift was reduced compared to spraying without air-assistance. Young (1991) also used a wind tunnel to study drift from boom sprayers. He found that air-assistance by means of a slotted duct ('Hardi Twin') significantly

reduced the drift potential, especially regarding fine and very fine sprays. With a twin-fluid nozzle ('Airtec') the drift potential could be diminished by adjusting both air and liquid pressure, in such a way that the spray quality was affected while the flow rate remained constant (and low).

### *Orchard crops*

Göhlich, *et al.* (1979) showed that a higher level of kinetic energy of air-assistance in conventional orchard sprayers increases both the emission to the air and to the ground. Higher air velocities increased drift. They postulated that an increased number of droplets reaches greater heights where they are more prone to be picked up by prevailing air currents.

In vineyards, tangential fan sprayers essentially match crop size and foliage density much better than conventional axial fan sprayers. Deposition on the leaves' back sides was improved while ground deposition and spray drift was reduced, both in high volume (1000 l/ha) and low volume (150 l/ha) application (Bäcker, 1986). Optimal deposition was reached when the air flow was directed 30° to 45° backwards, with respect to the side-ward direction. It was hypothesized generally that, using a tangential fan sprayer, a 25% reduction of the applied amount of chemicals could be achieved without loss of crop products.

#### *6.2.6 Electrostatic spraying and drift*

Metz, *et al.* (1987) studied the interaction between mechanical, dynamical and electrical forces of charged droplets and of the charged spray cloud. It appeared that smaller droplets have a better charge-mass ratio than bigger ones. Field and laboratory experiments showed that under 3 m/s air velocity the increase of deposition of electrical charged droplets is sufficient.

Miller (1988) found that electrostatic charging had different effects on air-borne drift when the wind conditions changed. At higher wind speeds air-borne drift close to the nozzle tended to be increased by charging, but at lower wind speeds there was some tendency to reduce drift. These results were consistent with observations in other studies, and were possibly caused by mutual repulsion of droplets and propelling some smaller, more highly charged droplets, upward.

Western and Hislop (1991) found increased emissions to the air when electrostatic charges were added to air-assisted sprays in wind tunnel experiments. They suggest that this might be caused by the mutual repulsion of small highly charged droplets which drive the spray upwards.

#### *6.2.7 Physical properties of the spray and drift*

Water-based sprays are prone to evaporation. This reduces the size of the droplets during

their flight, which makes them more sensitive to drift. Oil reduces evaporation by producing a thin film around the droplet. When the viscosity is increased, droplet size increases, and drift is decreased. Drift reduction substances tie the droplets through a polar bond. This reduces drift, but gives problems with the attachment of the droplets to the crop.

Wodanegeh and Matthews (1981) investigated whether addition of oil could reduce drift. They studied drift from 1) water plus 5% wetting agent, 2) water plus 20% oil and 3) undiluted oil which was sprayed with spinning discs. The droplets in their study had a VMD of 40-50  $\mu\text{m}$ . Drift was reduced when oil was added to the water and was lowest for the undiluted oil.

Gilbert and Bell (1988) concluded that drift can be reduced by limiting the amount of volatile materials in spray liquids. While a 100  $\mu\text{m}$  non-volatile (oil) droplet would theoretically be expected to drift about 30 meters when released from three meters high into a 10 km/h wind, a water droplet of the same size containing a 0.1% non-volatile material could evaporate down to a 10  $\mu\text{m}$  diameter within 15 seconds and then could drift over two kilometers.

Maas and Krasel (1988) measured drift from sprays with various types of herbicides and with various additives. Both affect drift results greatly. Drift decreases with the following herbicides as indicated: Basta  $\approx$  Roundup  $\approx$  U 46 DP-Fluid  $>$  Arelon fl.  $\approx$  Fervin  $\approx$  Fusilade  $\approx$  Gesaprim  $\approx$  Gesatop  $\approx$  Goltix  $\approx$  Kerb 50 W  $\approx$  Tribunil  $>$  Certrol H. Additives could reduce drift down to 25%, where drift reduction for Lipomel  $>$  Citowett  $>$  CuCoMix. Various countries recommend the use of the additive Hyspray when spraying herbicides, because this would increase the effectiveness. Maas and Krasel (1988) measured increased drift levels when this additive was applied with all herbicides tested, except for Certrol H and Goltix. The authors do not indicate which properties are altered by the use of the herbicides or additives.

# 7 Measuring techniques

Various aspects of pesticide sprays and droplets were reviewed in the preceding sections. How the various aspects are measured is presented in this section. We review the techniques used 1) in measuring the drop size, velocity and direction, 2) in determining the spray distribution on a macro and micro scale and 3) in studying drift behavior.

## 7.1 Measuring drop size, velocity and direction

Spray droplets are so small that they cannot be studied directly. Basically two different approaches have been used:

- the droplets are magnified before they are analyzed, or
- they are indirectly analyzed by determining their effect on electromagnetic waves.

Traditional techniques involved the collection of the droplets on suitable sampling surfaces (such as magnesium oxide coated slides, water-sensitive paper and oil matrix) and subsequent sizing. Those surfaces all suffer from reduced collection efficiency of smaller droplets (Arnold, 1983). Newer techniques allow 'in-flight' measurements.

Young, *et al.* (1987) and Hart and Young (1987) measured size, velocity and impaction of droplets with various techniques. They measured the diameter of individual droplets, collected in a 10 cm Petri dish, with a microscope fitted with a calibrated graticule. The Petri dish contained a medium consisting of two layers of silicone oil with viscosities of 100 and 20,000 cSt. They used a 2.D optical array spectrometer to determine the size and velocity of falling droplets. They studied characteristics of impacted droplets (such as contact angle, retention, wetting and drying behavior) on wheat leaves by scanning electron microscopy fitted with a cryogenic preparation chamber and a cathodoluminescence detector.

Matzen and Jørgensen (1990) used high speed filming at 4000 pictures/s to follow droplets of 50  $\mu\text{m}$  and larger. Size, velocity and direction before and during deposition could be followed. They compared the results with traditional measuring methods. Chrome cote paper and water sensitive paper proved to be efficient methods, while PVC bars are less suited since part of the spray reflects from its surface. The efficiency of silicon oil in a petri dish as a measuring method depends on its viscosity.

Various researchers (Arnold, 1983; Cowell and Lavers, 1987; Porskamp, 1989) measure drop sizes with the aid of laser (diffraction) technology (Malvern Particle Sizer). Arnold (1983) concluded that readings made in the edges of the liquid sheet are susceptible to errors from two main sources: 1) increasing droplet dispersion with distance from the nozzle; and 2) sampling errors due to the width of the laser beam. The former effect is likely to be predominant at distances in excess of about 20 cm in a direct line from the nozzle and the latter effect is of importance close to the nozzle. The Malvern Particle Sizer preferentially measures the longest axis of particles in its beam. This may cause errors when making measurements close to the region of sheet disintegration. Arnold

(1983) recommended to maintain a distance of 30 cm from the nozzle when measuring drop size spectra for flat fan sprays at 300 kPa laterally.

Arnold (1983) measured drop sizes of flat fan sprays with a Malvern Particle Sizer, laterally and transversely (through the major and minor axis of the fan, respectively). He concluded that lateral measurements give a good approximation to the overall droplet-size spectrum. They are, however, restricted to a limited distance from the laser beam, because of the risk of some spray reaching the optics of the system. Transverse central readings can be made at virtually any distance, but make no allowance for the larger droplets formed at the edges of the spray.

Western and Woodley (1987) measured sprays with an Aerometrics Phase Doppler Particle Analyzer (PDPA) and with a Malvern Particle Sizer. The PDPA instrument measures the drop size on the basis of the interference pattern formed as a drop passes through the intersection of two laser beams. The drop velocity is measured using laser/doppler velocimetry. They found very different drop spray parameters and concluded that this is caused mainly by the fact that the Malvern Particle Sizer is based on spatial sampling, while the Aerometrics PDPA employs temporal sampling. Spatial sampling of hydraulic nozzle sprays, which have a significant drop size-velocity correlation, results in an over-estimation of the small drop (<100  $\mu\text{m}$ ) component.

## 7.2 Measuring spray distribution

Different techniques are used to measure macro and micro scale spray distributions where

- the spray pattern produced by the sprayer forms a macro scale distribution, while
- spray deposits form a micro scale distribution.

### 7.2.1 Measuring spray patterns

Distribution patterns from sprayers are determined by volume or by weight.

Cowell and Lavers (1987) measured spray patterns from air-liquid atomizers with a Lurmark Spray Patternator with collection channels 5 cm apart.

Kümmel, et al. (1991) determined the vertical distribution pattern of air-assisted sprayers for trees with a 'lamellate spray-separator'. The system separated the liquid particles almost completely from the flow. The liquid fraction was collected at different heights in separate graduated cylinders. 80-90% of the sprayed volume was recovered. The authors assumed that the remaining 10-20% was lost through evaporation; most of this evaporation would take place during transportation from the sprayer to the separator, while a smaller fraction evaporated in the separator.

A 250 cm high measuring system for air-assisted orchard sprayers is described by Van Zuydam and Porskamp (1989). It measures both the distribution of the air velocities and the distribution of the spray liquid. Air velocities are scanned with 10 pitot tubes with

mutual vertical distances of 25 cm. These measurements are repeated at preset distances, so that they obtain a two-dimensional array of air velocity values. The direction of the air is determined with pieces of knitting yarn attached to the back of the pitot tubes. The spray liquid is collected on strips of filter paper at mutual vertical distances of 10 cm. The increase in weight of these liquid collectors is determined and processed by the computer. 80-98% of the liquid was recovered with this system. They suggest that the remainder is lost as a result of evaporation.

### 7.2.2 Measuring spray deposits

Last and Parkin (1987) reviewed the literature on measurements of spray deposits and concluded that volumetric analysis with fluorescent tracers is probably the most common technique in spray deposit research. Most of the analyses are volumetric with a spectrofluorometer. Information on droplet numbers, sizes and area covered, requires magnification of the drop image. Image analyses makes it possible to process droplet information rapidly and is more and more employed.

Schmidt (1980) showed that dyes, such as brillantsulfoflavin, reduce the surface tension of water considerably, while the surface tension of water-glycerine solutions was increased by the addition of various dyes. He also found that surface tension affects the drop size spectrum. A lower surface tension than water results in a smaller drop size spectrum at low pressures and in larger drop size spectrum at high pressures. The viscosity nor the density of the solutions were modified by the dyes which he tested in his study.

Fluorescent tracers which are used in volumetric deposit analysis include Saturn yellow fluorescent tracer (Wodageneh and Matthew, 1981), Lunar Yellow pigment (Cowell, et al., 1988), Uvitex (also referred to as HELIOS OB (Bryant and Courshee, 1985) and Univex (Afreh-Nuamah and Matthew, 1987), Tinopal CBS-X (Ciba-Geigy Dyestuffs) (Last and Parkin, 1987), fluorescein sodium salt, Aurora Pink E1 (Anderson, Hall and Seaman, 1987), Brilliant Sulvoflavine (Schmidt, 1980) and Brilliant Sulvoflorine (Ripke, 1990). Non-fluorescing tracers are sometimes added.

Last and Parkin (1987) also used fluorescent tracers with the microcomputer-based image analysis system which they developed to detect spray deposits on natural surfaces automatically. They concluded that special attention must be paid to the production of good images, since fluoresced light is generally of low intensity. They tested various fluorescent tracer on suitability in image analysis and found finely milled Tinopal CBS-X to be most effective as tracer for use in water. Good imaging optics and a sensitive camera are all important to obtain good image contrast. At application rates of 200 and 100 l/ha in wheat the extent of cover could be measured accurately. The deposits from these sprays did not necessarily consist of discrete droplet stains so that individual droplets could not be analyzed.

Anderson, et al. (1987) also found that the pigment particles were not always evenly distributed across the area of the dried down droplets. They used the insoluble fluorescent tracer Aurora pink E1 to determine the extent of coverage. The deposits were photographed with ultra-violet illumination. The percentage leaf coverage of dried deposits



was estimated with an Optomax Image Analyser Vids II System.

Afreh-Nuamah and Matthew (1987) added Sudan black dye besides the fluorescent tracer Uvitex to an electrodyn blank formulation. They also used a spray with the fluorescent tracer Univex in distilled water with nigrosine black dye. The dyes provided a good contrast with the kromekote cards on which the droplets were collected. This facilitated counting with an image analyzing computer (Optomax).

Jepson, *et al.* (1987) used an image analysis computer system to study 1) drop size distributions and 2) surface coverage. The system can process images from drops which are collected on various media such as MgO slides, other sensitive materials, photographs and fluorescent deposits on artificial and natural surfaces. The images can be captured with a video camera, or a light or scanning electron microscopy.

## **7.3 Measuring emissions**

### *7.3.1 Measuring drift*

Drift measurements are based on samples and give good indications on drift reduction potentials, but not of absolute quantities of drift (Göbel and Göhlich, 1989b; Gilbert and Bell, 1988).

Until recently, all drift assessment methods involved dyes or other indicators. They were either expensive or required relatively large inputs of labor. Göbel and Göhlich (1989a; 1989b) developed a thermoresistive drift assessment method which measures drift based on the temperature drop caused by the loss of heat during evaporation of spray droplets. They found that the integral of the temperature deficit was reproducible and independent of environmental conditions. The method can be applied as long as the air humidity is below 90%. The drift measurements need to be corrected when one of the very few plant protection chemicals with a high vapor pressure is used or when the spray contains evaporation retardants (see § 2.1). Göbel and Göhlich (1989a; 1989b) concluded that this measurement method leads to the same results as the conventional isokinetic drift probes which are based on fluorescent deposits.

Measurement techniques for quantifying drift have been developed based mainly on static line collecting surfaces. A major limitation to such techniques is the collection efficiency of these lines. The sizes of air-borne droplets at the collector site can easily be less than 40 µm. Such small droplets are difficult to collect efficiently on, for example, 2 mm diameter lines. This is especially true at low wind speeds (Miller, 1991).

Carlton, *et al.* (1990) investigated the optimum diameter of a cylindrical spray collector for aerial sprays with a VMD of 302-553 µm. They discussed the theoretical background of spray drop collection from which follows that larger droplets are collected more efficiently on smaller cylinders. This is the result of the distortion of a falling droplet which causes an increase in the projected (frontal) area in the direction of travel. They concluded from the theory that smaller cylindrical collectors, larger drops, and higher drop velocities should result in higher spray collection efficiencies. Experiments showed

that a 3  $\mu\text{m}$  diameter spider web fiber could collect water drops 250  $\mu\text{m}$  in diameter.

Western and Hislop (1991) measured drift from a spray solution of 0.025% w/v sodium fluorescein and 0.1% w/v Agral 90 in tap water. They collected the drift on horizontal two-ply Bri-nylon knitting yarn lines 7 m downwind of the atomizer at heights from 0 to 80 cm above the winter wheat crop in a spray chamber. They also used earthed spray collectors with the same knitting yarn lines in conjunction with 5 Amp fuse-wire. The fluorescein tracer was extracted in 0.05 M sodium hydroxide and measured by spectrofluorometry.

Ringel and Anderson (1991) collected drift on strips of filter paper and on cylindrical pipe cleaners. They used sodium fluorescein as tracer material. Analyses were performed with a Perkin Elmer Fluorometer.

Cooke and Hislop (1987) collected drift on a frame which was placed five meters downwind of the application path. This frame consisted of three cross-members at heights of 0.5, 1.5 and 2.5 m above the ground, each of which was fitted with six electrically (12 V) driven rods ('Rotorod' at 30 cm intervals. Drinking straws (7 cm x 0.28 cm diam.) were placed on each twin 'Rotorod' arm and rotated at 2 500 rpm. The two sprays were spiked with the separate pesticide markers cypermethrin and decamethrin. The deposits of these markers were extracted with HPLC-grade n-hexane containing 5% Analar acetone. Quantitative analysis was performed by gas-liquid chromatography using electron-capture detection. The two pyrethroids were separated on a fused silica (30 m x 520  $\mu\text{m}$ ) DBI phase Megabore column at 260°C.

During the first year of a study, Ripke (1990) collected air-borne drift on object slides (76 x 26 mm) at a height of 1, 2, 3, and 4 m above the ground. The object slides were fixed normal to the ground on masts which were placed with a distance of 15, 20 and 35 m from the treatment strip. During the second year he employed spherical 'drift collectors' with a diameter of 10 cm. These spheres weighed 15 g and consisted of 0.38 mm synthetic braided material which allowed the air to enter. Immediately after the experiments the drift collectors were placed in wide-mouthed bottles in which they could be transported without any disturbance. In the laboratory water was added to the drift collectors which were then shaken for 10 minutes, subsequently washed. The extract was analyzed with a fluorometer on concentration of the fluorescent dye Brilliantulfloflorin, which was added at a concentration of 0.1% to the spraying water.

Göhlich, *et al.* (1979) used an active and a passive drift measuring method to collect drift in combination with fluorescent tracers.

The active method consisted of a filter apparatus through which the concentrated air was sucked. It could be rotated horizontally with a wind vane, which directed the surface of the suction opening always normal to the existing wind direction. The suction velocity could be adapted to the existing wind velocity with the aid of a variable speed axial fan. This was installed behind the filtration surface. Such filter apparatuses were placed in the tree tops and at 0.1, 4, 8 and 12 m above ground level.

The passive method was based on deposition measurements. Sedimented droplets were collected with glass slides.

Gilbert and Bell (1988) concluded that the experimental methods in crop spraying should be standardized as much as possible. This would provide a common basis to separately gathered data so that meaningful comparisons could be made between independently conducted studies. They collected drift samples on vertical and horizontal polythene lines, absorbent paper strips, aspirated air samplers, and from the suits and respirator filters which were worn by bystanders. They used the aqueous spray tracers Lissamine Green (CI 44090) and Orange G (CI 16320), and the oil based tracer Waxoline Red O. They developed a method to estimate drift from various types of sprayers and under various conditions in field trials.

Earlier research indicated that magnesium oxide coated slides are inefficient collectors of smaller droplets. Wodageneh and Matthews (1981) used these anyway because they provide a uniform surface on which both water and oil based droplets could be sampled without the problem of differences in spread factor.

### *7.3.2 Measuring soil deposits*

Ripke (1990) first used object slides (76 mm x 26 mm) to collect emissions to the soil. The object slides were placed on the ground, in a pattern normal to the driving direction on the leeward side, at distances of 1, 2, 3, 4, 5, 10, 15, and 20 m away from the treatment area. In a later part of the study he used 30 mm wide filter paper on 20 m long wooden supports to collect soil deposits. He employed five replicates with a mutual distance of 2 m.

# 8 Theoretical background

## 8.1 Fluid mechanics of liquids

Stationary flow of the viscous fluid in horizontal pipes of a spraying machine is described by

$$\Delta p = \lambda \frac{l}{d} \cdot \frac{1}{2} \rho v^2$$

where

$\Delta p$  = pressure difference

$\lambda$  = drag coefficient

$l$  = length of the straight pipe

$d$  = diameter of the pipe

$\rho$  = specific mass

$v$  = average fluid velocity

In the literature laminar and turbulent flow is distinguished. The nature of the flow is conveniently described by Reynolds' number ( $Re$ ), which is a dimensionless number depending on object shape, object size and fluid parameters. Reynolds' number is defined by

$$Re = \frac{\rho v d}{\eta}$$

where  $\rho$  is the fluid density and  $\eta$  is the dynamic viscosity. (The sometimes used kinematic viscosity  $\nu$  is equal to  $\eta/\rho$ .)

For flow through cylindrical pipes:

–  $Re < 2300$  : the flow is laminar and stable,

–  $Re > 2300$  : the flow is turbulent and stable.

In laminar flow the drag coefficient  $\lambda = 64/Re$  for very smooth pipes (law of Hagen and Poiseuille). For 'technically' smooth pipes  $\lambda = 75/Re$ .

The drag coefficient for turbulent flow can be described by the law of Blasius (Eck, 1961):

$$\lambda = \frac{0,316}{\sqrt[4]{Re}}$$

All the above mentioned formulas are valid for straight pipes only. The pressure drop has to be corrected when the flow path is changed in direction and/or area by fittings such as junctions, inlets, outlets, nozzles, and obstructions. In those situations the additional pressure drop is calculated by:

$$\Delta p = \xi \cdot \frac{1}{2} \rho v^2$$

In literature the factor  $\xi$ , based on experiments, is given for many fittings and pipe configurations.

The fluid velocity  $v_0$  at the outlet of a pressure atomizer can be calculated using Bernoulli's law:

$$v_0 = \sqrt{\frac{2\Delta p}{\rho}}$$

The pressure difference  $\Delta p$  represents the liquid pressure in the supply-pipe minus the pressure loss due to the internal nozzle geometry. Generally, the fluid escaping through the small orifice does not fill the orifice cross-section entirely, but a contraction occurs. The cross-sectional contraction factor  $\alpha$  mainly depends on the nozzle geometry and may vary in practice between 0.6 and 0.8. The flow rate  $Q_0$  of the nozzle is then given by:

$$Q_0 = \alpha A v_0 = \alpha A \sqrt{\frac{2\Delta p}{\rho}}$$

where  $A$  is the actual orifice cross-section area.

## 8.2 Fluid mechanics of air

### 8.2.1 Fluid mechanical considerations of air movement

General aspects of fluid mechanics can be found in several handbooks on this topic (e.g. Eck, 1961).

In most practical cases air can be considered as an incompressible, low viscosity fluid. Theoretically, air flow thus can be described by the Navier-Stokes equations for incompressible fluids. In practice, however, these equations are too complicated to be solved analytically.

Air flow through channels or around objects can be laminar or turbulent. The state of flow (i.e. laminar or turbulent) depends Reynolds' number ( $Re$ ). For spherical drops moving through air Reynolds' number is defined by

$$Re = \frac{\rho v d}{\eta}$$

where  $\rho$  and  $\eta$  are air density and (dynamic) viscosity, respectively;  $v$  is the relative air-speed,  $d$  is the droplet diameter. Note that this equation is equivalent to Reynolds' number for fluid flow through pipes, however the used quantities have a different physical meaning.

For  $Re < 1$ , approximately, air flow around a droplet is laminar, while for  $Re > 1$  air flow becomes turbulent. Because air viscosity is low in the absolute sense, it is the major cause for turbulent flow occurring in almost all cases considered.

Forced air flow at high speed through some kind of channel is usually turbulent. Although all pressure losses are essentially viscosity based, in that case losses can be described conveniently by a frictional coefficient ( $\xi$ ) rather than viscosity (see § 8.1).

### 8.2.2 Droplet transportation

The transportation of droplets from the nozzle outlet until deposition involves the dynamic interaction of several factors (Elliott and Wilson, 1983):

- atomizer and application induced air flows;
- physical characteristics of the spray liquid;
- droplet evaporation;
- droplet sedimentation;
- wind turbulence.

Droplet trajectories are based on the interaction of three forces:

- gravitational force (causing sedimentation);
- aerodynamic drag (by airspeed and air turbulence);
- electrostatic force (in case of electrically charged droplets).

### 8.2.3 Gravitational sedimentation

Droplets falling under gravity in still air reach a certain constant velocity (the sedimentation velocity) which depends on droplet diameter. This sedimentation velocity results when the gravitational force and the aerodynamic drag force on the droplet balance. Larger drops have a higher sedimentation velocity than smaller drops (see Table 8). For drops smaller than 50  $\mu\text{m}$  in diameter the air flow around drops falling at sedimentation velocity is laminar. In this case the aerodynamic drag is described by Stokes' law (i.e. the drag is proportional to drop velocity). For larger drops the air flow behind the drops becomes turbulent, in which case the sedimentation velocity appears to be less than predicted by Stokes' law.

The time needed for droplets released at rest in still air to reach their sedimentation velocity increases rapidly with increasing droplet diameter. It is convenient to define a 'relaxation' time, defined as the time taken by the drop to reach 63% of the sedimentation velocity (see Table 8).

**Table 8** Relaxation times, sedimentation velocities and stopping distances<sup>1</sup> for water drops in still air at 1 atm and 20°C (Elliott and Wilson, 1983).

Drop diameter ( $\mu\text{m}$ )	Relaxation time (ms)	Sedimentation velocity (m/s)	Stopping distance <sup>1</sup> (cm)
10	0.31	0.0030	0.4
20	1.2	0.012	1.2
50	7.3	0.072	6.5
100	25	0.25	2
200	71	0.70	-
500	200	2.0	-

<sup>1</sup>) at an initial projection velocity of 20 m/s horizontally.

Droplets are usually projected with an initial velocity depending on liquid pressure and atomizer characteristics. Droplets projected horizontally in still air lose their initial velocity by the aerodynamic drag. The distance after which their horizontal velocity has vanished, has been termed 'stopping distance'. The stopping distance of larger drops at a

given initial velocity is longer than that of smaller drops (see Table 8). In case of droplets projected vertically downwards the term 'stopping distance' is related to the distance at which the velocity has decreased down to the sedimentation velocity.

Practical example: drops of 200  $\mu\text{m}$  diameter projected downward from a spray boom at 0.5 m are projected directly into the crop, while drops smaller than 50  $\mu\text{m}$  diameter acquire the local air velocity (usually directed backward with respect to the sprayer boom because of the forward driving speed) very soon after leaving the nozzle. Therefore the effective spray release height must be considered in any predictions of spray drift.

#### 8.2.4 *Entrained air stream*

The understanding of the droplet trajectories is complicated by the fact that the liquid sheet leaving the nozzle outlet with a high speed entrains the surrounding air creating local air flow circulations. Especially smaller drops are affected by this nozzle induced air flow and are thus unaffected for a while by the wind turbulence (Elliott and Wilson, 1983).

Himel (1982) reported that droplets smaller than 100  $\mu\text{m}$  diameter were transported in concert with 100  $\mu\text{m}$  droplets. This implies that these small droplets will deposit in accordance with the 100  $\mu\text{m}$  droplets.

Giles and BenSalem (1990) found that the entrainment rate was affected by the mean flow rate in intermittent spraying. Agreement between experimental and theoretical results could be obtained.

#### 8.2.5 *Atmospheric conditions*

Frictional drag causes wind speed to decrease closer to the ground. Wind speed can be approximated by a logarithmic dependence on height above the ground, and is scaled by the physical roughness of the ground surface. Therefore, drops falling at their sedimentation velocity will fall steeper when closer to the ground.

Since the wind speed varies with the height above the surface, shear stresses occur between neighboring air layers of different speed. These shear stresses cause frictional turbulence to occur (or 'eddies'). Typically for soil, grass or crop surfaces the eddy velocity is about 10% of the mean local airspeed.

Roughly four different atmospheric stability conditions can be distinguished:

- neutral: the eddies can be considered as circular turbulence;
- moderately stable;
- stable conditions: the vertical air movement is restricted (cool air is kept down by warm air above), causing a vertical flattening of the eddies; the eddy velocity is smaller than 10% of the mean local airspeed;
- unstable: the vertical air movement is enhanced due to buoyancy (warm air at the ground rising through cool air above), causing a vertical stretching of the eddies; the eddy velocity is larger than 10% of the mean local airspeed.

The logarithmic wind speed profile is valid in neutral stability conditions, and, with modifications, in moderately stable and unstable conditions. The logarithmic profile is not valid, however, at low wind speed or in strong inversion conditions (often experienced early in the morning).

In strong stability conditions vertical air movement is almost completely inhibited and adjacent air layers will slide over each other. The ground level air flow therefore is poorly defined and usually highly variable in direction.

Göhlich, *et al.* (1979) applied the meteorological term 'Stability Ratio' or SR, to characterize the stability of the air. It is calculated as

$$SR = \frac{T_2 - T_1}{\bar{V}_w^2}$$

Where

SR = Stability Ratio;

$T_1$  = Temperature at lowest measuring point, °C;

$T_2$  = Temperature at highest measuring point, °C;

$\bar{V}_w$  = Average wind velocity, m/s.

A positive SR indicates a stable layer with inversion, a negative SR refers to an instable turbulent layer, while a SR of approximately 0 symbolizes neutral, adiabatic weather conditions.

In accordance with the above, three relative drop sizes can be defined (see Figure 8):

1) 'large' drops:

- sedimentation velocity exceeds three times the eddy velocity;
- the drop trajectory is dominated by sedimentation;
- since sedimentation velocity depends on drop size, the drop trajectory through the air is depending on drop size.

2) 'small' drops:

- sedimentation velocity is less than 0.3 times the eddy velocity;
- the drop trajectory is dominated by air turbulence;
- the drop trajectory is independent of drop size.

3) 'intermediate' drops:

- sedimentation velocity and eddy velocity are of the same order of magnitude;
- the drop trajectory depends both on air turbulence and sedimentation.

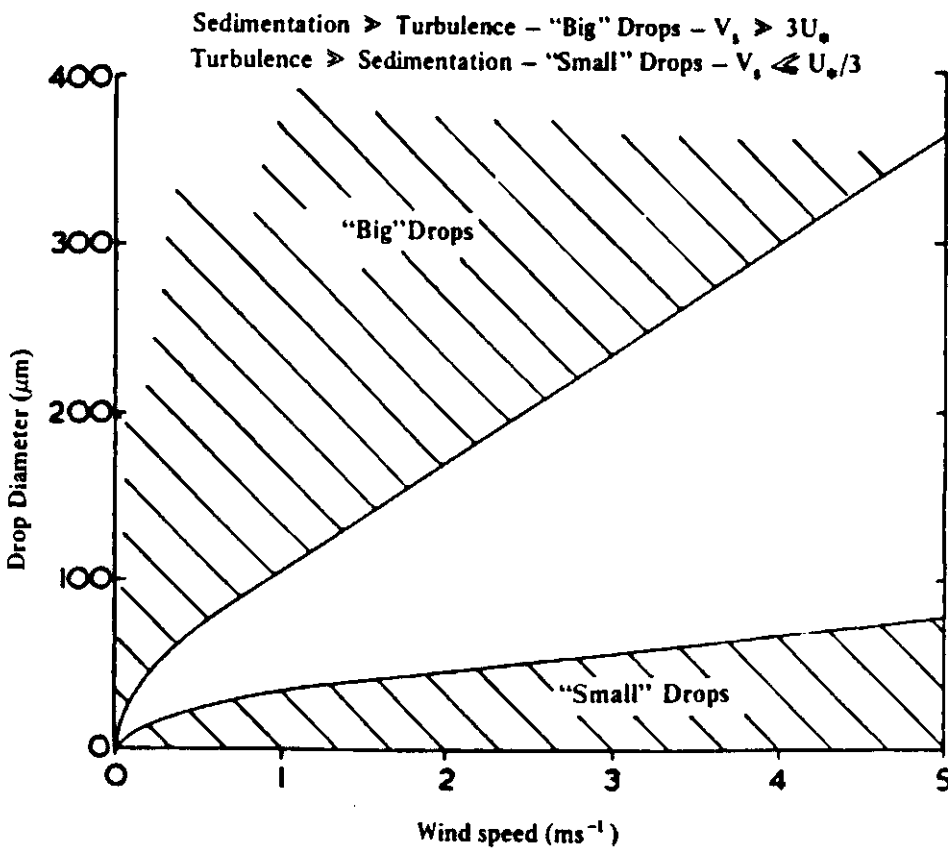
### 8.2.6 In-flight evaporation

Evaporation of drops involves both heat transfer and mass transfer processes. Generally heat transfer is from the surrounding air to the drop, while mass transfer evidently is from the drop to the surrounding air by convection and diffusion. The rate of evaporation depends on (Lefebvre, 1989):

1) The physical properties of the air:

- pressure;
- temperature;





**Figure 8** Areas of dominance of sedimentation on turbulent transport.

- thermal conductivity;
  - specific heat;
  - viscosity.
- 2) The relative velocity between the drop and the surrounding air.
- 3) The properties of the liquid and its vapor:
- density;
  - vapor pressure;
  - thermal conductivity;
  - specific heat.
- 4) The initial condition of the drop:
- drop size;
  - temperature.

Since heat exchange and vaporization depend on drop surface area and are enhanced by air moving across this surface, it is obvious that the rates of heat and mass transfer depend on Reynolds' number, whose value changes during the droplet's lifetime continuously because of the changing drop diameter and drop velocity. After a certain time each drop reaches a kind of steady-state at the 'wet bulb' temperature corresponding to the prevailing conditions.

Smaller drops evaporate faster than larger drops. In steady-state evaporation the drop diameter  $d$  decreases with time according to the following relation (Lefebvre, 1989):

$$d^2 = d_0^2 - Kt$$

where  $t$  is the time,  $K$  is the rate of evaporation, and  $d_0$  is the drop diameter at time  $t=0$ . The rate of evaporation depends mainly on partial vapor pressure (or in the case of water: the relative humidity), besides depending on thermal conductivity of the air, the heat of vaporization of the liquid and the liquid density (Hartley and Graham-Bryce, 1980). Typical values of  $K$  for water drops (initial diameter 500  $\mu\text{m}$ ) averaged over their total lifetime are 1200, 800 and 400  $\mu\text{m}^2/\text{s}$ , at 17%, 33% and 59% relative humidity, respectively (calculated after Elliott and Wilson, 1983).

The transient or 'cooling-down' period before the steady-state is reached is proportional to the square of the drop diameter.

Relative velocity between drop and surrounding air enhances the rate of evaporation ( $K$ ). Such convective effects, however, do not affect the drop temperature nor the cooling-down period. For small droplets that soon gain the mean local air velocity, convection effects are limited to the effect of local air velocity disturbances (turbulence). Generally, convective effects during the time needed for a drop to reach a constant sedimentation velocity can be ignored since this time is usually much smaller than droplet lifetime (Elliott and Wilson, 1983).

Since the evaporative decrease of drop diameter is faster for smaller drops, evaporation affects not only the median diameter (e.g. VMD) of a spray of drops but also the spread of drop sizes. Monodisperse sprays show a decrease of median drop diameter, however, the VMD of a spray containing a wide range of drop sizes may increase because of the vanishing of small drops.

The rate of evaporation of drops of a particular size depends almost completely on the difference between the dry and wet bulb temperature (directly related to the relative humidity of the air) (Hartley and Graham-Bryce, 1980). The lifetime  $t_e$  of a water drop can be approximated by

$$t_e = \frac{d^2}{78\Delta T}$$

In this equation  $t_e$  is in seconds,  $d$  is the drop diameter in  $\mu\text{m}$  and  $T$  is the temperature difference in  $^\circ\text{C}$  between wet and dry bulb.

Experiments with mixtures of water with various formulations showed that the evaporation rate remained approximately equal to that of pure water, until almost all the water had evaporated. The weight of the remaining drop approximated the weight of the involatile fraction of the initial droplet (Elliott and Wilson, 1983). These results support the 'solid core' model, which assumes all involatile parts to be concentrated at the center of the drop, while the rate of evaporation equals that of the surrounding liquid.

### 8.2.7 *Drop coalescence*

Drops moving at different speeds may collide. Whether or not collision leads to coalescence depends on drop diameters, their relative velocity, and the collision angle (Lefebvre, 1989). Collision frequency also depends on the number density of the spray and the time available to collisions. Therefore coalescence is most likely in dense spray clouds far from the atomizer.

### 8.2.8 *Drop size and deposition*

Small droplets adapt quickly to local air velocity changes and easily flow around leaves. Therefore, small droplets penetrate the plant's foliage much better than large drops. Turbulence formation at the back side of a leaf improves the deposition of small drops at the back side. This turbulence formation is enhanced by leaf surface roughness (Rosswag and Moser, 1987).

To optimize deposition, air velocity, direction and volume should be adapted to the plant size and foliage density (Bäcker, 1986).

# Appendix a

## Fan types and characteristics

Generally, three types of fans can be distinguished (Bäcker, 1986; Rosswag and Moser, 1987; Miller and Hobson, 1991) (see also Figure 9):

– Axial fans:

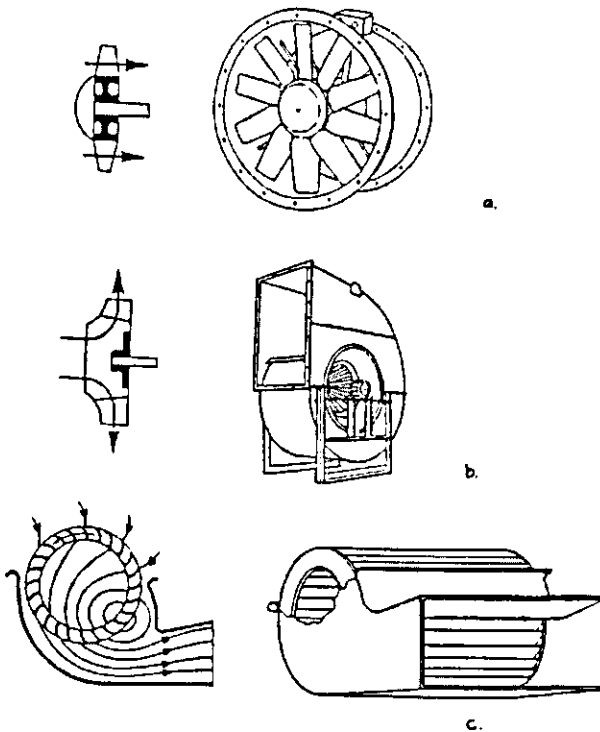
Air enters the fan axially and leaves the fan either axially or radially (after redirection of the air stream). Output air velocity is mediate (35 m/s), while output volume is high (typically 30,000 m<sup>3</sup>/h). The air velocity profile at the outlet may be uneven. The pressure resistance which can be overcome is medium to low.

– Radial (or centrifugal) fans:

Air enters the fan axially and leaves the fan tangentially after cylindrical acceleration. Output air velocity is very high (40-80 m/s), while output volume is low (4000 m<sup>3</sup>/h). The pressure resistance is higher than with axial fans.

– Tangential (or cross-flow) fans:

Air enters and leaves the fan tangentially. Output air velocity is low (20-30 m/s), while output volume is high (10,000 m<sup>3</sup>/h). The air velocity profile at the outlet is rectangular and evenly distributed. Pressure resistance is low. Power efficiency is low (ca. 30%). The rotational speed of the fan is limited, mainly because of out-of-balance effects at high speeds. Confusingly, sometimes the term cross-flow fan is also used for orchard sprayers with axial fans and high vertical air outlets.



**Figure 9** Characteristics of fans used in crop protection; a. axial fan, b. radial fan, c. tangential fan.

The air output is most efficiently controlled by varying the rotational speed of the fan, since the required fan power is highly dependent on rotational speed. Air output control by baffling the fan inlet or outlet, or adjusting the blade angle (for axial fans) should be avoided.

Loss of fan power efficiency is minimal when the following aspects are considered (Rosswag and Moser, 1987; Miller and Hobson, 1991):

- the air at the fan inlet should have no swirl;
- the air entrance of the fan should be placed into the forward direction;
- the fan outlet should be straight for at least two times the fan diameter;
- redirection of the air stream should always take place gradually without any sharp edges;
- additional turning vanes at bends may prove to be useful;
- changes in cross-section should always be gradually;
- air entrance and exit should be spatially separated to avoid immediate re-entry of air from the output (especially in the case of orchard sprayers).

# Summary

In view of the increased concern for the environment, the Dutch government aims to reduce the total consumption of crop protection chemicals with a minimum of 50% by the year 2000. A literature research was carried out to review the nowadays used application techniques and the relation to efficacy and drift.

Depending on the type of pest to be controlled, pesticides can be classified in nematocides, insecticides, acaricides, fungicides and herbicides. These chemicals reach their target by direct contact (contact pesticides) or after being taken up and transported through the plant (systemic pesticides). Pesticides are available in different formulations, depending on 1) the physical-chemical properties of the active ingredients and 2) the requirements posed by the various application techniques and machineries. The physical-chemical properties of a formulation can be changed by the use of adjuvants (e.g. wetting agents, evaporation retardants, drift retardants).

A pesticide usually is applied together with a carrier material. Mostly water is used as a carrier, while in air-assistance forced air also can be considered as a carrier. The present trend is towards application techniques using continually lower carrier volumes. The choice which application technique is best depends on the type of pest, the crop species and the pesticide formulation.

Application equipment for crop protection can be divided roughly in field equipment and orchard sprayers. Target oriented application techniques include row and band spraying, weed wiping and intermittent spraying. Various tools can be used to assist the application, e.g. air-assistance, aerofoil booms, recirculation techniques, electrostatic drop charging, and crop tilters. Dosage control is aimed at by injection techniques and the use of spraying computers.

With row and band techniques the spraying is restricted to the row and the area between the rows, respectively. Recently intermittent spraying is introduced, in which sensors are used to detect the target. The dose rate is controlled by continuously turning the sprayer on and off.

With air-assistance the placement of the nozzle with respect to the air flow, the air flow direction and its power are of main importance for successful application. Recirculation techniques are promising but may request special crop planting methods. Electrostatic spraying can be divided into three methods: corona charging, induction charging and contact charging. Each methods has its own advantages and limitations. Problems with respect to flow and clogging are important with injection techniques.

All techniques and tools have their own advantages and problems. Research results in the literature sometimes are contradictory.

Sprayed pesticides consist of a large amount of drops of various sizes. Drop size and velocity depend on the type of atomizer, the orifice size, the atomizer spray angle, the spraying pressure, and the physical properties of the pesticide itself.

With respect to atomizers, the following types can be distinguished: pressure atomizers, air-liquid atomizers, and rotary atomizers. The latter two have the advantage that they

operate even at low flow rates. However, results in the literature may point at the necessity of a strict control of application conditions within a narrow margin. A smaller orifice, a wider spray angle and a higher spraying pressure all reduce the drop size. Surface tension, viscosity and density are the most important physical properties which affect drop size. These properties can be manipulated by the addition of certain adjuvants. Generally a better coverage of drops on the target can be reached using a finer spray, which however may give rise to increased drift. Especially the leaves' undersides can only be reached by small drops. Unfortunately, little is known of the relation between drop size and biological effect.

The performance of crop protection equipment must be evaluated in light of biological effectiveness. Biological effectiveness is related to distribution and deposition over the crop. Important aspects are crop penetration, impaction, adhesion, retention and wetting. Crop penetration is greatly affected by the type of crop and crop density. Small drops can easily move around leaves and thus penetrate the crop. Large drops, however, penetrate the crop by forcing their way through. Impaction and adhesion of drops depends on drop size, surface tension of the spray liquid, surface roughness of the leaf and elasticity of the drop surface. Large drops may shatter on impact, or may be reflected. Small drops easily adhere to the leaf surface. After adhesion to the leaf large drops may run off easier than small drops. Wetting increases the retention of drops to the leaves. Generally, the distribution over the crop appears to be better with smaller drops. Air-assistance may improve distribution provided that air flow rate, velocity and direction is adapted to the situation. Sprayer boom movements result in a worse distribution over the crop. Horizontal movements (yaw) more severely affect distribution than vertical movements (roll).

In pesticide spraying the term drift is commonly used to refer to: the transport of crop protection materials through air movements to the direct surroundings of the treated plot. The extension of drift depends on wind speed, temperature, relative humidity and crop morphology. Wind is the major climatic factor affecting drift. Temperature and relative humidity mainly affect evaporation of small drops while spraying. However, evaporation continues after the drops have deposited. A dense crop foliage filters the spray cloud better than an open crop, thus giving rise to less drift.

Drift is greatly depending on the application technique chosen. Factors such as drop size, velocity and direction, boom height and orientation, driving speed and application rate may affect the amount of drift. Drops smaller than about 150  $\mu\text{m}$  are drift-prone. Atomizers with a larger spray angle will show in itself enhanced drift, because of the production of smaller drops and a less mean downward drop velocity. However, with these atomizers boom height can be less, which may lead to a net decrease of drift. A higher driving speed and a lower application rate both increase drift.

Drift is affected by the use of air-assistance or electrostatic spraying. Air-assistance usually gives rise to decreased drift, but the air flow rate, velocity and direction should be adapted to the application technique chosen and the crop morphology. However, presently the optimal settings in different situations are not known. Contradictory results have been reported on drift with electrostatic spraying. Whether or not drift is reduced may depend on other factors, such as wind speed and drop size.

Drift can be reduced by the use of adjuvants, but this may affect drop size and may give

problems with the attachment of drops to the crop. Non-volatile carrier materials (e.g. oils) are able to reduce drift adequately.

Measuring techniques concern 1) drop size, velocity and direction, 2) spray distribution and 3) drift behavior. Traditional time consuming collection techniques for drop sizing are gradually replaced by 'in-flight' laser techniques. Also high-speed filming is used. With these newer techniques besides drop size also velocity and direction can be obtained. Spray distribution measurements include measurements of the spray pattern produced by the sprayer, and those of the spray deposits in the target area. Commonly spray deposit measurements are carried out using fluorescent tracers. Sometimes also dyes are used. Tracers or dyes may affect the surface tension of the spray liquid, thus affecting the drop size spectrum. Recently image analysis systems are used to study drop size distribution and surface coverage. Drift assessment methods usually involve tracers or dyes and various kinds of drift collectors. No standard drift assessment method has emerged yet. The present methods may give satisfactory results in comparing different techniques, however, no reliable measurements can be made on their own.

Spray flow through the sprayer system can be adequately described theoretically. Droplet transportation from the atomizer to its place of deposition can in general terms be described by gravitational, aerodynamic and electrostatic forces. Exact calculations are hindered by aerodynamic interactions between different drops, air turbulence and other atmospheric conditions, such as atmospheric stability and evaporation.



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# Index

Active ingredient	8	Electrostatic spraying	23
Additives	10	Evaporation	64
drift reducing	53	Fans	20
surface-active agents	10	axial	68
surfactants	38	centrifugal	68
wetting agents	10	cross-flow	68
Air foil (Aerofoil)	20	power efficiency	68
Air-assistance	20	radial	68
drift reduction	51	tangential	68
ducts	21	Fluorescent tracers	56
Application		Formulation	8
application rate	11	Image analysis	56
equipment	15	Injection	24
Atmospheric stability	63	Laser/doppler velocimetry	55
Atomizers		Malvern Particle Sizer	54
air-liquid	28	Nozzles	
CDA	29	anvil	28
placement	30	deflector	28
pressure atomizers	27	flat fan	28
pressure-swirl	27	hollow cone	28
rotary	29	impact	28
spinning disc	29	solid cone	28
spray angle	30	twin-fluid	28
wedge-shaped	29	Pesticides	8
Closed Loop Spraying (CLS)	22	acaricides	12
Contact angle	40	contact	11
Coverage	11	fungicides	13
Crop penetration	38	herbicides	13
Crop tilter	19	insecticides	12
Diameter		systemic	12
Mass Median Diameter (MMD)	32	Phase Doppler Particle Analyzer	55
Number Median Diameter (NMD)	32	Pipe flow	
Sauter Mean Diameter		laminar	60
(SMD, D32)	32	turbulent	60
Volume Median Diameter		Recycling	
(VMD, D50)	32	collector system	22
Drift	45	reflector system	22
direct	45	tunnel sprayer	22
drift potential	45	Recycling system	22
indirect	45	Relative Span (RS)	33
Drift collectors	57	Sedimentation velocity	62
Drop size	31	Spray quality (BCPC)	34
physical properties	35	Sprayers	
Dyes	56	band sprayer	18



cross-flow sprayer	17
row sprayer	18
tower sprayer	17
Spraying computers	26
Stability Ratio	64
Stopping distance	62
Surface tension	40
Target sensing	19
Tray spraying	22
Wind speed profile	63

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