CHARACTERISTICS OF SWIRL TYPE NOZZLES FOR SPRAYING MACHINES

by

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Introduction

Modern development in the field of plant protecting machines in characterised by a striving towards better qualitative and economic parameters of the work spent on the production of plants and towards a greater coverage. To increase the coverage and to make work more economical, the amount of chemicals spread over unit of area is reduced to 50 — 5 dm^3/ha. Biological examinations into the efficiency of the spraying work have verified that in some cases—for instance in spraying herbicides, fungicides, defoliating agents—the success of work depends on the size of the droplets and their distribution [1], [2]. The mean size of the drops produced by the multipurpose devices varies within wide limits, 10 and 600 μm.

The endeavour to minise the amount of liquid sprayed and to meet the requirements set to the jet, viz. a set of drops of varying average size, within a narrow spectrum and better distribution—opened up a new era und ushered in new methods in atomizing, and stimulated the development of hydraulic spray heads. In spite of the spread of new drop forming fan spray atomizers, in the greater part of spraying work hydraulic spray heads are still used. The advantages they offer are simple layout, small power demand and economical operation, are likely to keep the hydraulic spray heads on the scene for a long time to come.

From among the known hydraulic atomizing devices plant protecting machines use the centrifugal and impinging type heads in the first place. Of the two the centrifugal types are more versatile and they are, in fact, widely used with machines operating along combination atomizing methods.

1. Principle of operation

In centrifugal spray heads, drop formation takes place through the rotatory movement of the liquid to be atomized in the swirl chamber.

With an ideal fluid the flow in the chamber of the sprayhead conforms to the laws of free circulation; the relations describing it are known. With real fluids, however, the evolution of free circulation is hampered by boundary and internal frictions (Fig. 1). Due to the small dimensions of sprayheads, the effect of the boundary layer forming along the walls of the swirl chamber is substantial.

While the rotation speed in the axis $(\overline{xx})$ of the swirl chamber of an ideal fluid (v_c) would be infinite, due to the above outlined effects, that of a real fluid shows a moderate increase in the direction of the axis of the sprayhead, still of a degree which is sufficient to cause an air core to form in the chamber. This air core comes about across the nozzle in the lower portion of the swirl chamber and, in favourable cases, extends quite up to its upper wall.

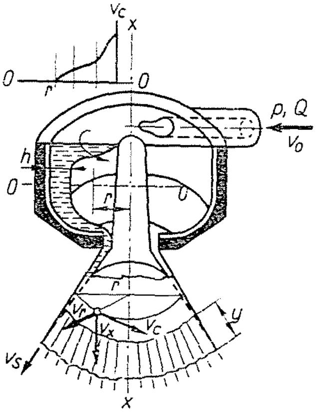

Fig. 1. Operation of a centrifugal sprayhead

Due to the rotary movement and the air core, the fluid will eject from the nozzle across an annual cross section and spread out into a coherent conical capillary film. This film is formed by the capillary forces acting over the surface, thinning away with increasing distance from the sprayhead. The movement of the particles in the film is characterised by axial (v_x), radial (v_r) and tangential (v_c) velocity components; close to the sprayhead, the flow of the fluid particles of the film is laminar, farther away from it, due to the disequilibrium of the capillary forces in the liquid sheet (see zone y) it first becomes disturbed then turbulent. Owing to the effect of the energy of the turbulent flow, fluid particles will break away from the fringes of the thinned-out sheet and continue on their path in the form of droplets. In the zone y, the speed of the film rotation (v_c) will first gradually decrease; the rotation then stops altogether and the detaching drops move at a speed of v_s in the direction of the generatrix of the spray cone.

2. Criteria, operation

As is known the spray devices used in the practice of plant production have three basic tasks:

- to produce droplets,
- to transport, and, eventually
- to distribute them

over the surface of the vegetation. With hydraulic sprayheads—and among them with centrifugal atomizers—the distribution of the drops takes place simultaneously with the formation of drops while the transport of the detaching droplets is achieved by kinetic energy. The movement of the drops is influenced to a negligible or more appreciable degree (depending on their size) by gravitation and by the resistance of air.

Another important requirement is to control the quantity of the atomized liquid within wide limits. This demand is satisfied, in swirl-type sprayheads, by the change of nozzles and the adjustment of the pressure of feed.

Centrifugal sprayheads are operated mostly in serially connected groups. The heads must be arranged in a way that ensures an optimum distribution of the liquid and maximum coverage.

As will be seen, the technique of spraying sets many and various requirements to the design and operation of sprayheads, in fact more than in any other field of application.

How far they meet these requirements we may conclude from the hydraulic and atomization characteristics, and from the parameters relating to the penetration zone and the spray pattern. In the last ten years we have conducted many investigations to clear the basic relationships between geometric and operating parameters of various centrifugal sprayheads. The relationships used here are established as results of these investigations.

3. Sprayhead characteristics

The performance of sprayheads can be judged by their characteristics. To plot these curves numerical values of the following main parameters should be determined:

- liquid consumption, Q dm^3/min
- coefficient of discharge, μ
- length of the fluid film, l mm
- the cone angle of the spray, θ deg
- mean drop diameter, d μm
- the specific atomizing work, A cmkp/cm^2

The variation of the feed pressure and the change of nozzles must be illustrated as a function of the feed pressure and the nozzle diameter.

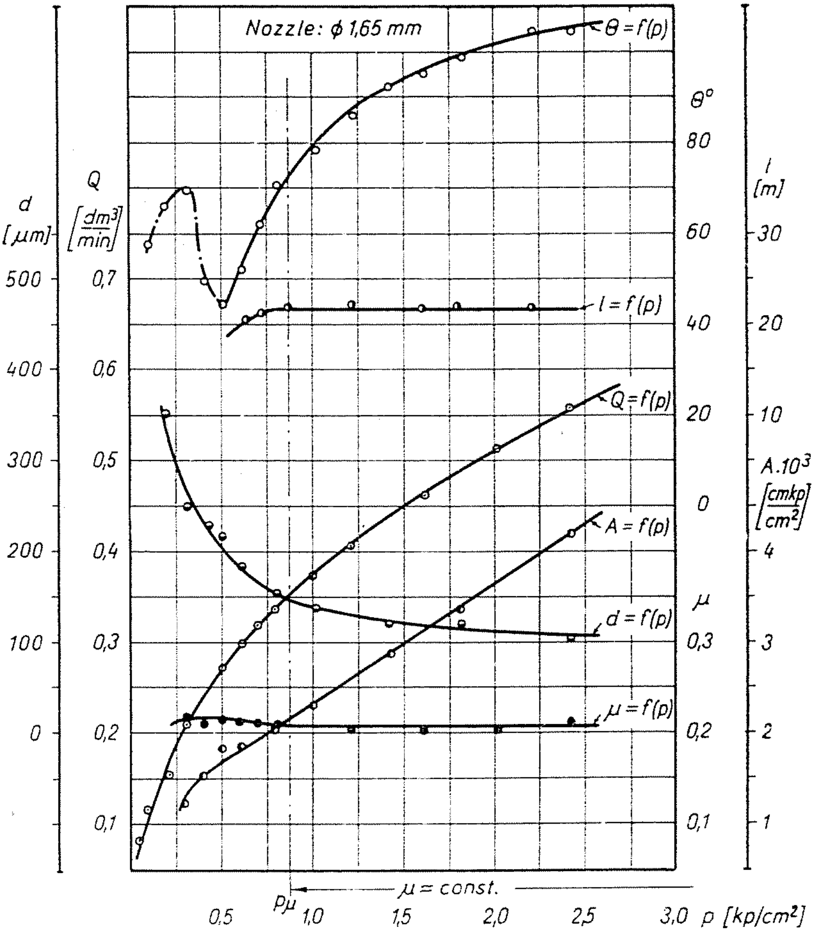

Fig. 2. Important curves for sprayheads in function of the pressure: Q fluid consumption: θ spray angle; l length of fluid film; μ coefficient of discharge; d linear mean drop diameter: A specific atomizing work. Water temperature: 21°C

Applying pressure on the swirl-type sprayhead, first a disturbed jet will emerge from its nozzle then, with increasing pressure, a closed air core will evolve below the nozzle which at first expands then spreads out. This phenomenon is best illustrated by the variations of the spray angle which increases until the air core is open, subsequently it diminishes, to increase again (see Fig. 2). Attaining a value of μ = constant, the spray angle and the cone angle of the sheet will be practically equal, the sheet is spread out, its length (l)—the generatrix of the cone—remains unchanged.

With increasing feed pressure the linear mean drop diameter will first rapidly diminish and in the pressure range of μ = constant, the curve flattens out. Looking at the drop curves obtained for different sprayheads, it was found that the range in which it is worthwhile to try to vary the drop size by the adjustment of pressure falls between

$0.3\ p\mu$ downwards and
$3.0\ p\mu$ upwards

of the "stabilizing" $p\mu$ pressure value. The variations achievable, however, are rather limited.

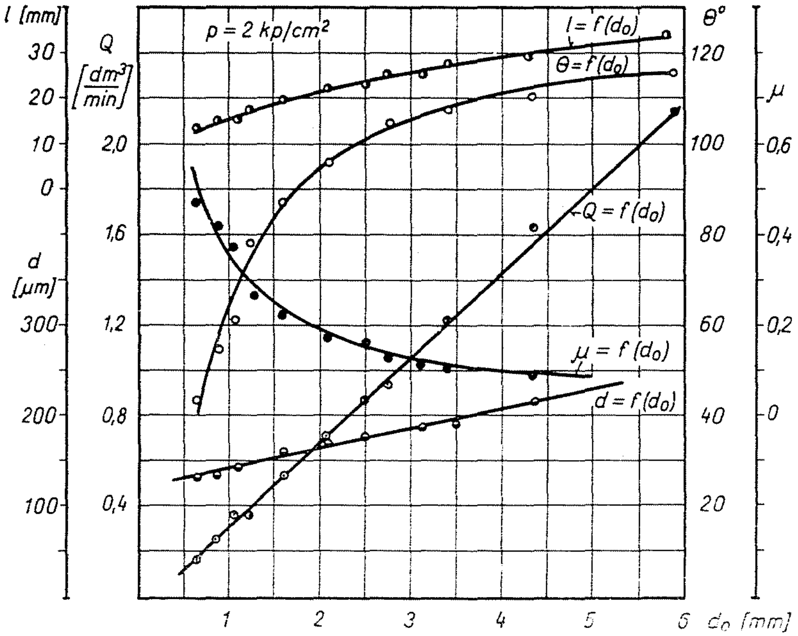

Fig. 3. Sprayhead curves in function of nozzle diameter: Q liquid consumption; θ spray angle; l length of film; μ coefficient of discharge; d linear mean drop diameter. Water temperature: 12°C

In the pressure range of μ = constant the specific atomizing work (the work necessary to produce a drop of 1 cm² surface) varies along a straight line. Therefore, in informative tests for the selection of the sprayhead, it is sufficient to determine the mean drop diameter and the specific atomizing fork for two widely different pressure values. Connecting them with a straight line, we can calculate the drop sizes in the respective pressure range.

Studying sprayheads fitted with different nozzles under constant pressure, we made the following experience:

Towards larger nozzle dimensions the values of liquid transport and the mean drop sizes vary with a linearly increasing tendency (Fig. 3). Initially the spray angle increases at a fast rate but later on the upwards slope of the curve becomes moderate. Experience has proved that it is impracticable to use nozzles of a diameter larger than 3.5 mm in order to increase the spray angle. The coefficient of discharge decreases hyperbolically, the generatrix of the spray cone varies with a slight slope.

Studying the curves of the two figures plotted for the main drop sizes, we may safely state that the simultaneous variation of feed pressure and of nozzle diameter may produce the desirable drop size even in the range of μ = constant.

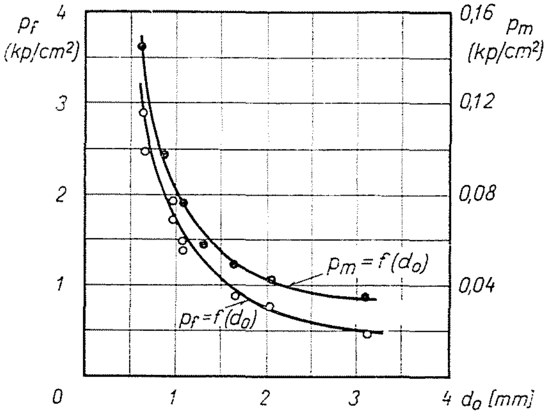

Fig. 4. Lowest pressures required to form air core and spread of film (p_m, p_f), in function of the nozzle diameter. Water temperature: 12°C

Vörös [3] studied the air core forming in the nozzles of centrifugal sprayheads. He found that in water, the air core evolves already at rather low pressures. With suitable circulation the swirl hole may extend up to the top of the chamber, along the nozzle axis.

According to observations the minimum pressure which produces the air core (p_m) is characteristic of the circulation in the swirl chamber. With identical nozzle dimensions, that sprayhead will produce finer droplets in which the pressure p_m is lower. The pressure required to spread out the spray film (p_f) is important from the viewpoint of the operation since it is at this pressure that the μ = constant range is reached; the range in which the drops detaching from the film move approximately in the direction of the generatrix of the cone.

The pressures p_m and p_f closely depend on the nozzle diameter (Fig. 4). The curves in the Figure were plotted according to measurements carried out on the same sprayhead, fitted with nozzles of different diameters. It was found that with increasing nozzle diameters the pressures p_m and p_f drop rapidly. This phenomenon comes in good stead in plant spraying machines, when the sprayhead performs preatomization only.

With increasing viscosity of the fluid, higher pressures are required to form the air core and to spread the film.

4. The coefficient of discharge

The coefficient of discharge in sprayheads is the ratio of actual to theoretical fluid consumption:

$$\mu = \frac{4Q}{d_0^2 \pi \sqrt{\frac{2g}{\gamma} p}}$$

where

Q the actual liquid consumption in cm^3/sec
d_0 nozzle diameter, in cm
g the gravitational acceleration, in cm/sec^2
γ the specific gravity of the fluid, in kp/cm^3
p the total pressure ahead of the spray head, according to Bernoulli's Equation, in kp/cm^2

The knowledge of the discharge coefficient is needed primarily to calculate the liquid consumption of the sprayhead. While in theory it can be derived on the basis of the geometric dimensions of the head, due to the quality of the surfaces in direct contact with the fluid and to inaccuracies in manufacture, dimensioning does not yield satisfactory results. The known dimensioning methods and the relationships established by dimensional analysis, namely, will enable to obtain approximate results with that design only and in that dimensional range, in which the measurements had actually been carried out.

The coefficient of discharge in centrifugal sprayheads may vary within wide limits. For example, in heads with 1.5 mm diameter nozzles, intended for the same job, the coefficient of discharge varied between $\mu = 0.2$ and 0.57. Of course, discharge coefficients with the same nozzle diameter may be greater or smaller than this value.

The only way available to us at present to establish safely the discharge coefficient is by measurements. In sprayheads fitted with exchangeable nozzles the relationship between the discharge coefficients and discharge ports, illustrated in the logarithmic scale, yields a straight line (Fig. 5).

The relationship between the coefficients of discharge and the discharge ports can be written down with the following equation:

where

$K\mu$ constant
d_0 the nozzle diameter in mm

The exponent in the numerator can be substituted in the equation with a value of

$x \approx 0.86$ if l/d_0 is constant and with
$x \approx 1.0$ if l is constant

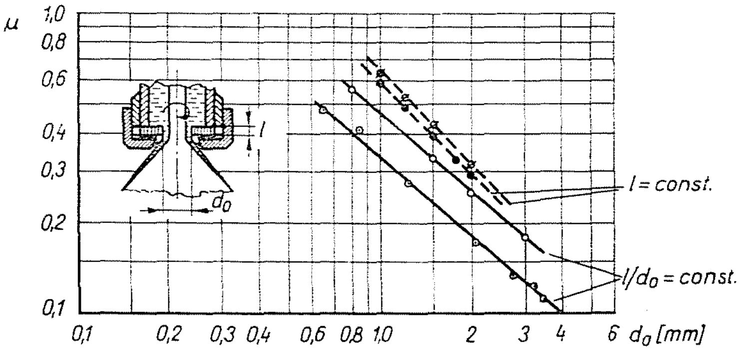

Fig. 5. Change of the coefficient of discharge as a function of the nozzle diameter. Water temperature: 19°C

$$\mu = \frac{K\mu}{d_0^x}$$

In possession of the discharge coefficient for one nozzle size, the relationship enables its calculation for different nozzle sizes with a fair degree of accuracy.

From the discharge coefficient of the preaheads we may conclude also at the drop forming effect. With identical nozzle dimensions the head whose discharge coefficient is lower will produce finer drops, a larger cone angle and smaller penetration zone.

Several researchers sought for relationships between the discharge coefficient and the coefficient of filling of the nozzle port [4], but they arrived at informative results only.

5. Selection of nozzle capacities

The spray booms of spraying machines are suitable for the atomization and dispersion of liquids at different rates, viz. the consumption of the sprayheads fitted to them is adjustable in a defined range ($Q_{\min} - Q_{\max}$). Making use of the equations quoted in the previous chapters, the liquid consumption of the heads fitted with nozzles of different dimensions can be calculated from the relationship:

$$Q = \frac{\pi}{4} \cdot K\mu \cdot d_0^{(2-x)} \sqrt{\frac{2g}{\gamma} \cdot p} \, .$$

Since the sprayheads must be matched with the feeding pump, the method to be used in selecting the nozzle capacities is as follows:

Using the above relationship we can calculate the values of liquid consumption for a number of nozzle sizes once on the basis of the lowest feed pressure necessary to operate the sprayhead, and once with the maximum feed pressure economically obtainable from the pump, and plot the data in a chart (Fig. 6). The straight line obtained for the lowest pressure should be above the curve of liquid consumption calculated with the pressure values (p_f) required to spread the liquid sheet. In possession of the minimum and maximum liquid consumption, the vertical ordinates of the stepped chart will indicate the requisite nozzle dimensions. To maintain the necessary fineness of droplets in the largest nozzle, a higher minimum pressure should be taken into consideration.

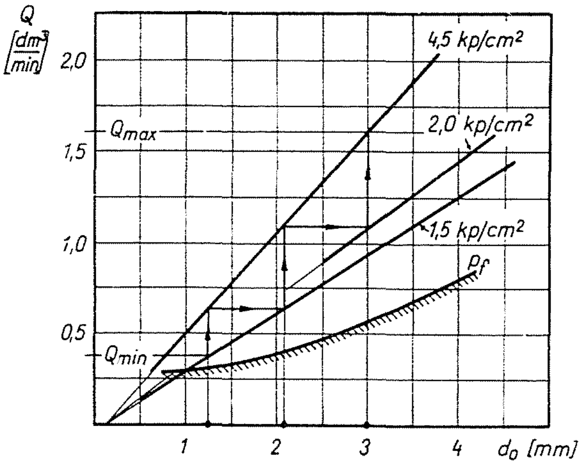

Fig. 6. Determination of nozzle capacities

According to experience the required spraying jobs can be implemented with 3—4 stages.

6. Atomization

The appraisal of the atomizing effect of the sprayheads demands utmost attention. Since the methods used in taking drop samples and their processing greatly influence the examination results, it would seem necessary to describe them, to enable the correct evaluation of the measurement results.

In our examinations the drops were caught up in silicone oil of suitable viscosity [5] passing the sampling vessel below the spray at a uniform speed. The drop sample was then recorded on photographic film and manually counted. We neglected the drops below 30 microns in size, as according to Stobwasser's observations made in 1959 the drops below 20 μm do not deposit on the vegetation [6]. This finding was verified by the tests performed by the Spraying Systems Co. in recent years, which set the lower size limit of useful drops atomized in hydraulic sprayheads at 20—30 μm. The neglection of the very small droplets is justifiable also because they represent a minimum of liquid, even if present in very large numbers.

6.1. Drop diameters, drop spectrum

The size of drops in the jet varies within relatively wide limits. Characteristic of sets of drops are the medium, equivalent and characteristic diameters.

The medium drop diameters divide the set of droplets into two equal parts—be the number, the surface, the volume or the mass of the drops concerned. The equivalent drop diameters may substitute the set of drop with their full value in all phenomena related to the jet, for instance, their movement, the incidence of the drops, evaporation, coverage, etc. The characteristic drop diameters are suitable for the qualification of the jet in part or as a whole. Such are the Sauter diameters, the diameters indicated by the maximum of the distribution or of the frequency curve, the diameters that can be calculated from the Mugele-Evans relationship, etc. In some cases the same drop diameter may satisfy the criteria of two types of diameter simultaneously.

In judging the quality of spraying work the coverage on the foliage is of a decisive importance. Since in the coverage the linear dimensions of the precipitating drops are taken as the effective size, it is mostly important to determine the linear mean value of the useful part of the set of drops. The set of drops may be characterised by frequency and by cumulative curves (Fig. 7). Since the drops below 30 μm are disregarded, the frequency curves will cover a narrower spectrum and the cumulative curve will have a steeper slope.

In comparative tests as to the drop forming effect it is customary to determine the volumetric mean and the Sauter diameters for the entire, or for the useful range.

6.2. Specific atomizing work

Under specific work of atomization the work required to create unity of drop surface is meant. In hydraulic atomizers this parameter can be calculated from the relationship

$$A = \frac{1}{6} \ \mathrm{pd} \ \ \mathrm{cmkp/cm^2}$$

where

p the total pressure ahead of the sprayhead, in kp/cm^2
d the linear mean drop diameter, in cm

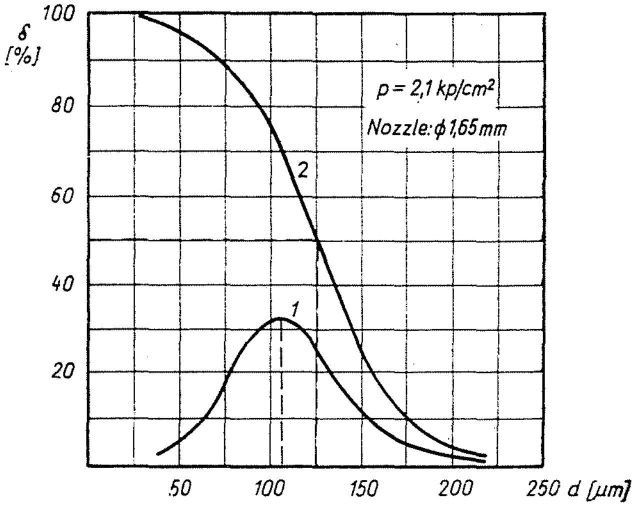

Fig. 7. Curves for the spectrum of drops: 1. distribution of frequency curve; *2.* cumulative curve. Water temperature: 21°C

In the examination of sprayheads it is important to determine the specific atomizing work for the estimation of the efficiency of drop formation. Its values, as seen previously, are arranged along a straight line in the range of μ = constant, depending on the feed pressure. The neight and bending angle of the line is characteristic of the atomizing performance of the sprayhead (Fig. 8).

The equation indicating the variations of specific atomizing work, in function of pressure, is as follows:

$$A = A_0 + \varepsilon p \ \ \mathrm{cmkp/cm^2}$$

The lower A_0 values can best be measured in the low-pressure sprayheads producing fine droplets, the highest A_0 values in high-pressure large-penetration-radius heads. In sprayheads with the same size of nozzles higher A_0 values give a steeper straight line viz. higher ε values. The straights for the specific atomizing work measured with different nozzle diameters, and constant nozzle length to diameter ratio, start from the same A_0 point.

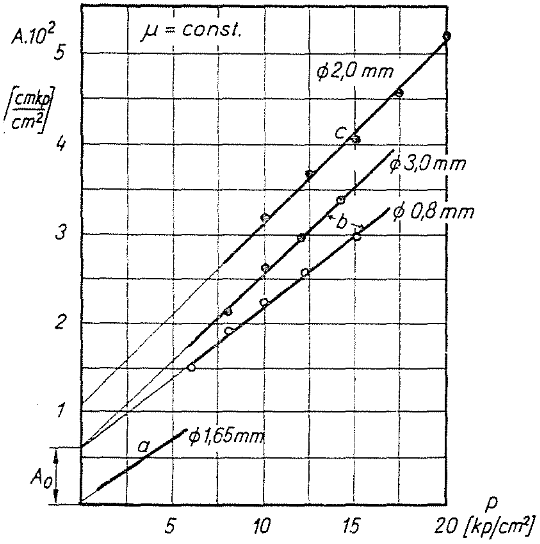

Fig. 8. Variations of specific atomizing work in function of the pressure in different sprayheads: *a)* fine atomizer; *b)* medium pressure; *c)* sprayhead to treat trees. Water temperatures: 21, 18, 20°C

Table I

Data obtained with centrifugal sprayheads and atomization

Denomination	Feed Press $p_ü$	Nozzle diameter d_0	Axis of specific atomiz. work $A_0 \cdot 10^2$	$\xi = \frac{\sigma_f}{A_0} \cdot 100$ atomizing coeff. $\varepsilon \cdot 10^2$		Minimum drop size $d_{min} = 6\ \varepsilon$ μm
	kp/cm²	mm	cmkp/cm²	%	cm	
Swirl-type fine atomizer	1.5— 6	1.65	0.090	8.14	0.137	82
Swirl-head type atomizer	6—12	0.80 3.00	0.656	1.11	0.156 0.191	93 115
Tree-protecting swirl-type head	10—35	2.00	1.070	0.68	0.204	122

Dividing the surface tension of the atomized fluid by A_0 we obtain a dimensionless number which characterizes the drop forming work of the sprayhead:

$$\xi = \frac{\sigma_f}{A_0} \cdot 100\% .$$

The relationship permits the calculation of relatively small ξ values since the energy uptake of the head had been related to the surface of the useful set of drops only. Alongside their surface, also the kinetic energy of the drops is important. This, however, is not included in the ξ coefficient.

Comparing the above two equations of the specific atomizing work, the mean diameter of the useful set of finest drops produced by a sprayhead is obtained at $p = \infty$.

$$d_{\min} = 6\,\varepsilon\,[\mu m]$$

This value is the asymptote of the function $d = f(p)$ which is well approximated already at normal pressures. The more important data bearing on the atomization work in some sprayheads have been compiled in a table.

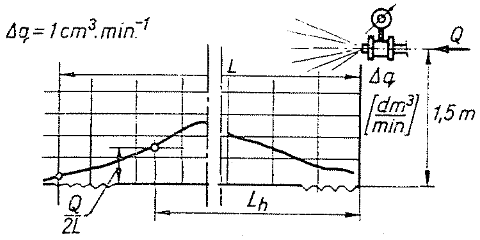

Fig. 9. Interpretation of the penetration zone and the effective penetration zone (L, L_h)

7. Penetration zone

The problem of the penetration zone emerges in the first place in connection with the taller plant cultures. There is no generally accepted measurement method to determine it. We interpret these two essential parameters in the following way:

the penetration zone is the distance between the 10 cm wide horizontally arranged trough collecting 1 $cm^3 \cdot min^{-1}$ liquid, and the nozzle of the horizontally positioned sprayhead mounted at a height of 1.5 m above ground;

the effective penetration zone, on the other hand, is the point of intersection of the fluid distribution curve plotted with the above assumption, and the horizontal straight line determined by the half of the mean distribution value $Q/2L$, calculated from the rate of liquid consumption (Fig. 9).

The method described above is suitable for the examination of the factors influencing the penetration zone and for the performance of comparative tests. The effective spray distance of the heads under operation can be established for any given case by the examination of the biological effects.

The penetration zone is influenced by all those factors which have a bearing on the drop size, the velocity of drop movement and its direction. Most important among these factors are

— the feed pressure
— the cone angle of spray
— the nozzle dimensions (liquid consumption).

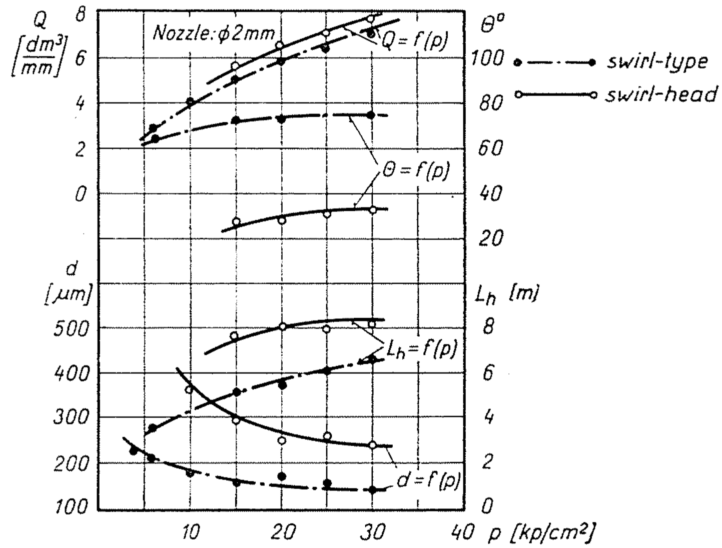

Fig. 10. Curves for high-pressure sprayheads in function of the pressure: Q = fluid consumption: θ = spray angle; d = linear mean drop diameter; L_h = effective penetration zone. Water temperature: 20°C

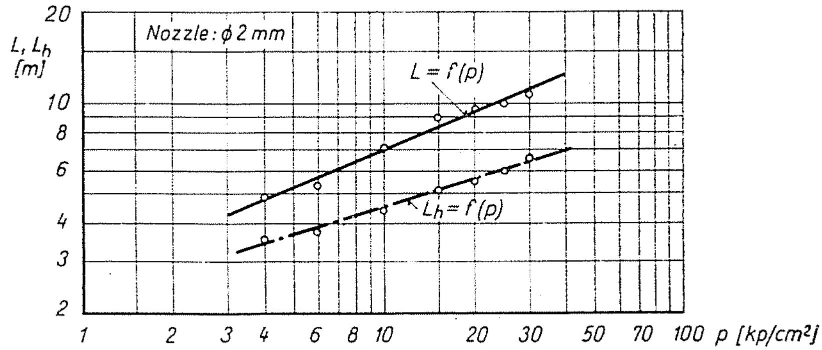

Fig. 11. Variation of penetration zone and effective penetration zone L, L_h, in function of pressure. Water temperature: 20°C

The influence of feed pressure and spray cone angle upon the effective penetration zone is shown in Fig. 10. Reducing the spray cone angle to half, the effective penetration zone between the pressures 15 and 30 kp/cm² increased by 2.8—2.0 m. The figure shows also that in the better sprayhead, at pressures of above 15 kp/cm², the effective penetration zone does not vary considerably. The more than 8 m zone was attributable, not lastly, to the fact that the mean drop diameter could be maintained at values of above 230 μm.

The relationship between feed pressure, penetration zone and effective penetration zone shows mostly a parabolic character (Fig. 11). It was also observed in several cases that with increasing pressure, diminishing the drop sizes—not only have the values of the effective penetration zone not increased but they actually diminished.

The influence of the nozzle diameter upon the penetration zone is shown in Figure 12 plotted on the basis of sprayheads of different types with large penetration radii. The chart shows that there is a small part of the set of drops which, depending on the pressure and the nozzle dimensions, can be caught up at an approximately equal distance from the sprayhead. This means that whereas in the range between 30 and 170 deg. the cone angle of spray has no appreciable effect on the penetration zone, it has a considerable influence upon the values of the effective penetration zone.

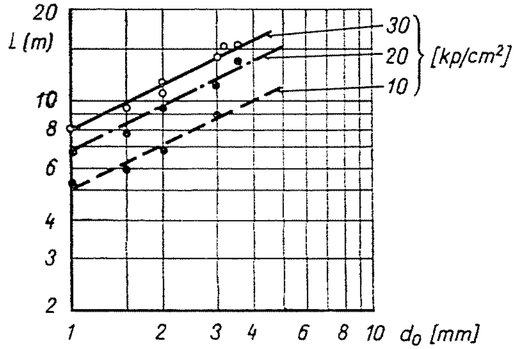

Fig. 12. Variations in the penetration zone in function of the nozzle diameter, with differen pressures. Water temperature: 20°C

To achieve a large effective penetration zone, the swirl-body sprayheads with conical chamber are better suited. The angle enclosed by the axis of the sprayhead and the entry of fluid must be less than 45°. The cone angle of the centrifugal chamber should, therefore, be chosen between 50 and 60°.

For the spray cone angle in heads designed for large penetration zones the values between 40 and 50° are best, because they ensure a satisfactory zone of coverage.

To vary the penetration zone, swirl inserts may be incorporated, which modify the pattern of circulation.

The requirements set to penetration zone—if there are no essential constrains for the operation of the sprayhead—can be mostly met with feed pressures of 25 kp/cm^2 or below. Fine droplets and large penetration zone together cannot be achieved with purely hydraulic atomizers.

Summary

The paper deals with the swirl-type spray heads of plant protecting machines which produce a hollow jet of liquid. It studies the variations of their more important parameters in function of the nozzle diameter and the supply pressure. It establishes a functionality between the coefficient of discharge and the nozzle diameter and suggests a method for the correct selection of the nozzle. It evaluates the drop forming effect of the sprayheads according to the average size of drops, spectral curves, the straight line of the specific atomizing work, and a dimensionless number. It points to some regularities between the main characteristics of the spray head and the penetration zone.

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