U.P.B. Sci. Bull., Series D, Vol. 80, Iss. 1, 2018 ISSN 1454-2358

EXPERIMENTAL RESEARCHES REGARDING THE DISPERSION ANGLE OF THE NOZZLE JET FROM SPRAYING MACHINES

Mihaela ROŞU (NIŢU) [1], Tudor CĂSĂNDROIU[2], Mihai-Gabriel MATACHE [3], Valentin VLĂDUŢ [4], Augustina PRUTEANU[5]

During the working process achieved by the spraying machines, an important role is that of the nozzles, which transform the spraying liquid substance in a drops jet of different dimensions, in the shape of a cone with a certain angle at the top. The size of this angle plays an important role in the process of covering the spraying surfaces and in placement of nozzles along support lance fitted on the spraying machine. The size of nozzle jet angle depends on the physical properties of the spraying substance, on nozzle geometry and on the functional characteristics of the system. In particular for every substance, angle size depends on the working pressure and nozzle diameter.

In the paper are presented experimental results obtained from measurements achieved with three different commonly used commercial substances and six types of nozzles used on current machines. With this data, the mathematical model proposed in a previous work by the authors was tested. Effective mathematical models that have been proposed provide a good prediction of the nozzle jet angle. The estimated values compared to experimental data correspond to a correlation coefficient R=0.91 – 0.97, at a variation coefficient under 5% for major researched cases.

Keywords: spraying machine, nozzle, angle jet, phytosanitary treatment

1. Introduction

Our health is indissoluble linked to the health of soil and plants providing us food products [1].

The use of pesticides is an integral part of modern agriculture and contributes to the productivity and the quality of the cultivated crop. It has been estimated that the use of agrochemicals prevents a loss of up to 45% of the world food supply. On the other hand, the increasing use of crop protection products is one of the rising environmental concerns [2].

[1] Phd. Student, National Research - Development Institute For Machines And Installations Designed To Agriculture And Food Industry, Bucharest, Romania, rosumihaelan@yahoo.com
[2] Prof., Emerit, Dep. of Biotechnical Systems, University POLITEHNICA of Bucharest, Romania, cctu39@yahoo.com
[3] Ph.D. eng., National Research - Development Institute For Machines And Installations Designed To Agriculture And Food Industry, Bucharest, Romania, gabimatache@yahoo.com
[4] Ph.D. eng., National Research - Development Institute For Machines And Installations Designed To Agriculture And Food Industry, Bucharest, Romania, valentin_vladut@yahoo.com
[5] Researcher, National Research - Development Institute For Machines And Installations Designed To Agriculture And Food Industry, Bucharest, Romania, pruteanu_augustina@yahoo.com

Development and modernization of agriculture is a natural and necessary process. We cannot imagine raising the quality of life if agriculture is not stimulated to produce as much as possible and at high quality. [3]

Agriculture development is influenced by natural, technical and socio-economic factors. Technical factors have an important role in increasing production, through mechanization, use of chemicals, irrigation, etc., phytosanitary protection occupying a very important place. [3]

An important factor in continuous increase of the quality of products obtained by economic agents is constituted by maintaining the conformity of plant protection equipment. Thus, the purpose of a spraying work is to evenly deposit a maximum quantity of phytosanitary product at the place of treatment, respectively on the spayed surface [4].

Equipment for applying phytosanitary treatments usually consist of: clean water tank, solution tank, agitator, pump, valves, distributor, manometer, pipes, spraying boom, spraying heads (nozzles). These last ones (nozzles) directly influence the working process quality.

Spraying represents the process of decomposing a liquid jet into drops. By spraying, the liquid is dispersed in small diameter drops, but the average diameter of the droplets can be very different, from a few microns (μm) to 2 ÷ 3 mm [5].

The liquid jet spraying process has been studied by many researchers [6, 7, 8], the results obtained allow to conclude that the surface of the jet coming out of the nozzle orifice is subject to small disturbances. These small disturbances are due to fluid flow regime, friction forces, nozzle orifice oscillation and imperfections of its geometric shape, geometry of the edge of the nozzle, the presence of gas bubbles in the jet, mechanical impurities, etc.

The paper presents the experimental results obtained from measurements conducted with three different, most commonly used, commercially available substances and six types of nozzles used in current machines. This paper also presents on one hand, the measured value of the jet angle at the nozzle and the value of the nozzle jet angle estimated for the three types of solutions, and on the other hand, the mathematical model, which will allow the high accuracy estimation of the value of spraying the jet angle depending on the working pressure and nozzle diameter.

2. Materials and methods

We can analyse the process of spraying the liquid through the nozzle by analogy with the spraying of liquid fuels for the combustion substances [9].

Thus, we define spraying by the process that leads to the conversion of liquid jet into fine drops by passing the pressurized liquid through a nozzle. The surface tension forces of the liquid, which give it homogeneity, are cancelled by internal and external factors. In the initial area, the liquid fraction is dominant, the liquid being decomposed into bubbles and ligaments (non-spherical liquid particles). In the intermediary zone, of dense spraying, the liquid fraction has a smaller but predominant proportion. Here, a secondary fragmentation occurs and drop/drop interactions, such as collisions appear. In the diluted spraying area, spherical, well-formed droplets predominate, which interact strongly with the turbulent air jet. In general, spraying depends on the liquid pressure when passing through the nozzle, the liquid flow rate that determines liquid velocity through the nozzle, the geometric characteristics of the nozzle, the viscosity and density of the liquid.

So far, it has not been possible to establish the laws of complex spraying. Although the phenomenon of decomposing the liquid jet has been the subject of a series of theoretical and experimental researches in the last 100 years, there has not yet been developed a general theory on the basis of which it is possible to determine a priori the degree of spraying for different types of nozzles, liquid characteristics and working conditions.[9]

In order to establish the physical relations, the link between the quantities used to describe the spraying phenomenon, the theory of dimensional analysis can be used. This method is based on the fundamental theorem of dimensional analysis, Π theorem [10].

An important size in the nozzle's working process is the spraying angle which is the angle of the jet cone and indicates its flaring. The size of the spraying angle is dependent on the density of the liquid flow and is the measure of the tangential and axial components of the liquid droplet velocity [11, 12].

The spraying angle depends mostly on the type and size of nozzle orifice.

Liquid pressure has a significant effect on the size of the spraying angle (Fig. 1). In practice, the nozzle has the size of the spraying angle marked on it.

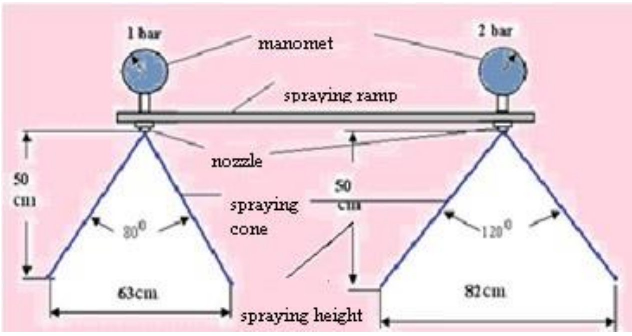

Fig. 1. Increasing the spraying angle together with increasing the pressure

Generally, liquids more viscous than water form smaller spraying angles, while liquids with lower surface tension than water are dispersed at larger spraying angles. Decreasing the spraying angle by 2÷10% leads to an unevenness of the distribution on spraying length of the lance.

To estimate the jet angle at the nozzle, in [13] the authors propose the following mathematical model:

$$\alpha = k\left(\frac{\eta_l^{\,2}\sigma}{D\rho_l}\right)^a \left(\frac{pD}{\sigma}\right)^e \tag{1}$$

where: α – jet angle, [rad]

η_l – dynamical viscosity of the liquid [P·s]

σ – superficial tension of the liquid [N/ m]

D – nozzle diameter, [m]

ρ_l – liquid density, [kg/ m^3]

p – liquid pressure, [Pa]

k – constant gain, [dimensionless]

a, e – power coefficient, [dimensionless]

Within the paper were used the measurement units frequently used in practice, namely: degrees, mm^2/s, mm, g/cm^3, bar.

Taking into account that dynamic viscosity (η_l), density (ρ_l) and surface tension (σ) are parameters that characterize a solution from the physical point of view, it shows a constant behaviour in constant given conditions.

Starting from relation (1), using the same liquid, results the function (2) for characterizing the jet angle, with two variable working measurement units: working pressure and nozzle diameter, new power coefficients x and y and another gain constant K which is depending on the physical properties of the fluid:

$$\alpha = f(K, x, y, p, D) = K\left(\frac{p}{p_0}\right)^x \left(\frac{D}{D_0}\right)^y \tag{2}$$

To emphasize the dimensionless character of angle size at nozzle, the working pressure and nozzle diameter were expressed in equation (2) related to initial reference sizes p_0 and D_0, considered: p_0 = 1 [bar]; D_0 = 0.0001 [m].

In order to obtain the values of coefficient *K*, *x* and *y* we propose the function *N(K,x,y)* as a sum of squares of the differences between the values obtained by applying the function f and the actual measured values α_i, p_i and D_i for the three aqueous solutions studied [10; 13; 14].

It results the function in the form:

$$N(K, x, y) = \sum \left[f(K, x, y, p_i D_i) - (\alpha_i) \right]^2 \tag{3}$$

For experiments, three commercially available aqueous solutions called solution 1 (active substance - nicosulfuron), solution 2 (active substance imidacloprid - imidacloprid), and solution 3 (active substance - glyphosan) were used, namely:

Solution 1 is a product conditioned in the form of a concentrated, fine, oily, homogeneous suspension for weed control, which is applied only with terrestrial spraying means provided with continuous stirring / homogenization systems for the spraying solution;

Solution 2 is a systemic insecticide for controlling larvae and eggs;

Solution 3 is a total, non-selective, non-residual herbicide in the form of a concentrated suspension with action on a wide range of weeds.

Density, viscosity and surface tension values of these three solutions have been determined with the help of the following equipment:

- Density meter, on the principle of the Archimedes law using a suitable floating body graduated in density units;
- "VIBRO VISCOMETER" viscometer, model: SV 10, which allows the dynamic viscosity of Newtonian fluids to be measured using vibrating elements (lamellae) with a vibration frequency of 30 Hz and a viscosity measuring range of 0,3 ÷ 10 000 mPa;
- SIGMA 703D tensiometer model, which allows the measurement of the surface and interfacial tension of liquids, with a surface / interfacial tension measuring range of 0.001 ÷ 1000 mN/m and a resolution of 0.001 mN/m.

The values obtained from measurements are given in Table 1, the values being determined at 20 °C, the optimal recommended spraying temperature.

Table 1

Physical proprieties of used substances

SOLUTION No.	DENSITY (ρ) kg/m^3	VISCOSITY (ν) mm^2/s = $\frac{\eta_l}{\rho_l}$	SURFACE TENSION (σ) mN/m
1	996.5	1.44	112.43
2	994.5	1.56	102.63
3	996.2	1.48	96.90

To perform nozzle jet angle measurements, a nozzle test stand equipped with a pressure regulator, manometer, pump, and two nozzle ports with 5 nozzles and drop stop (Fig. 2) was used.

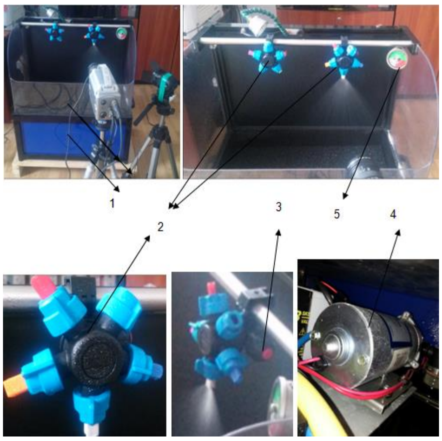

Fig. 2. View of the nozzle test stand

1 – nozzle test stand; 2 – nozzle support; 3 – drop stop; 4 – pump; 5 - manometer

For measurements were used plastic nozzles of different diameters, in the 0.1÷0.6 mm range (Fig. 3) with 0.1 mm steps and the three mentioned solutions.

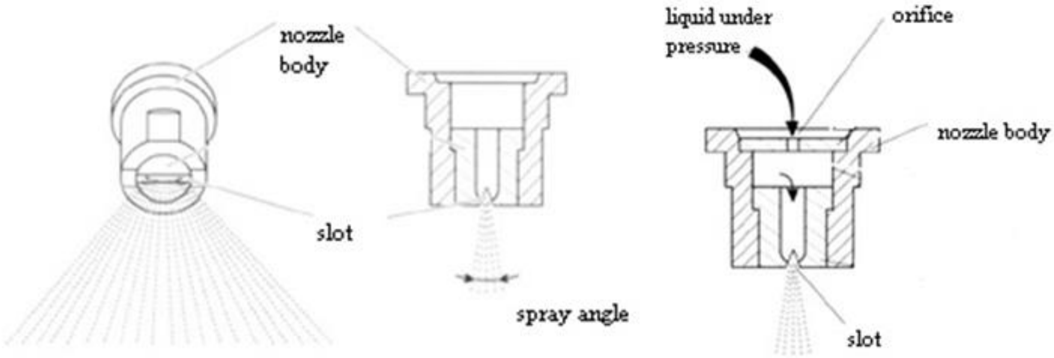

Fig. 3 Section view of a nozzle used in experiments [15]

To record the nozzle jet angle was used a high speed camera, Phantom V10.0, V 630 series (Fig. 4), which can record up to 10,000 frames per second and has its own processing software. Thus, during the working process, the nozzle liquid jets were filmed for each type of solution, using the 6 types of nozzles at 5 working pressures (1, 2, 3, 4, 5 bar). Each film was processed and afterwards, the nozzle spray angle was evaluated by its own software.

Fig. 4. View of Phantom V 10.0 camera

For determining the jet angle to be measured, a figure was selected from the program on which the jet angle generators were visually identified (Fig. 5). Four points (A, B, C, D) were chosen on these generators, so that the segments that connect them coincide with the angle generators. The nozzle jet angle is measured at the intersection of the two generators.

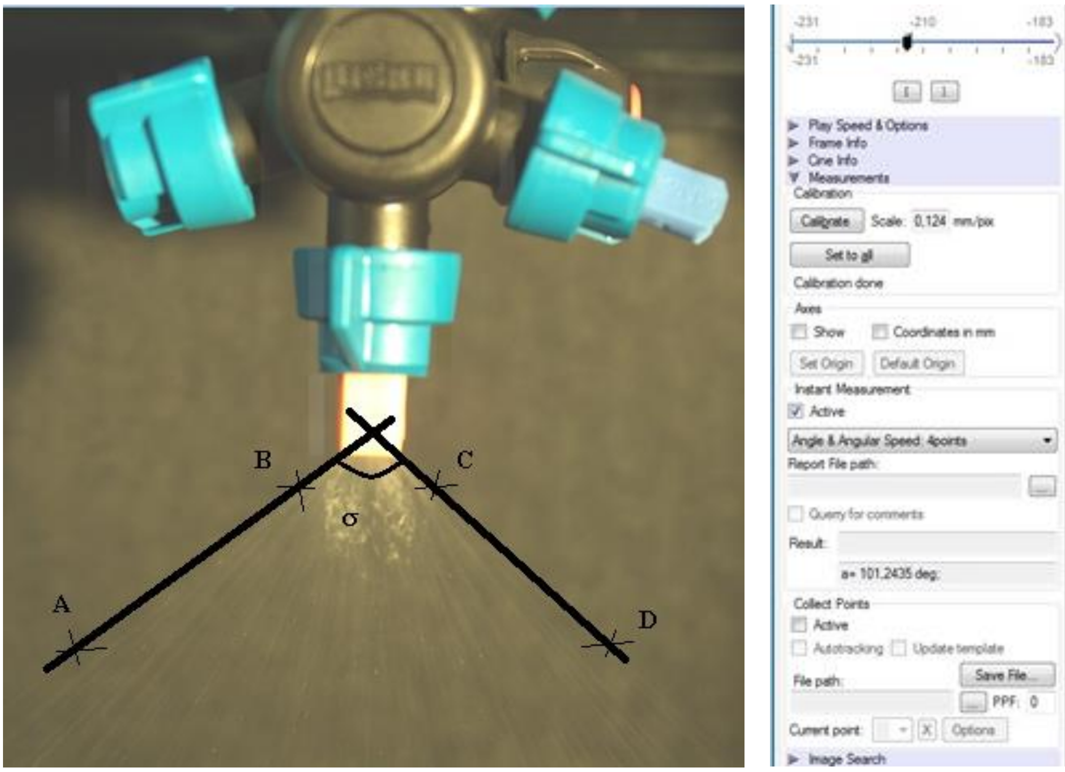

Fig. 5. Representation of the jet angle in 4 points

The same procedure was used for the six types of nozzles proposed for testing at the five different working pressures.

Several measurements for the same pressure had been previously performed, and the values are concentrated to a constant value found in any of the values in the repetitions, which required conducting a single measurement for each pressure and nozzle type.

3. Results and discussion

The data obtained from measurements regarding the α angle values of the jet at the nozzle for the 6 values of nozzle diameters depending on the pressure and for the three solutions are presented in Table 2.

Table 2

Variation of jet angle (α) measured depending on pressure for the 6 values of nozzle diameters and for the three solutions tested

Nozzle	Nozzle diameter D (mm)	Pressure (bar)	α spray angle values (degrees)			Coefficient of variation
			solution 1	solution 2	solution 3	
1	0.1	1	104.642	100.546	83.892	10.643
		2	112.16	100.982	96.64	7.269
		3	117.68	106.452	106.342	5.777
		4	119.384	110.59	108.316	5.024
		5	122.02	114.468	112.524	5.306
2	0.2	1	99.192	99.788	84.672	8.086
		2	108.93	111.162	97.502	6.474
		3	115.796	114.816	108.9686	3.161
		4	118.162	119.016	113.134	2.662
		5	120.73	120.882	116.576	2.629
3	0.3	1	93.722	97.898	87.1896	5.290
		2	104.77	105.17	96.188	4.675
		3	111.994	110.886	102.77	4.446
		4	115.68	114.466	109.71	2.667
		5	118.788	120.47	115.624	2.604
4	0.4	1	93.254	98.298	91.88	3.264
		2	102.68	104.634	103.328	0.918
		3	108.194	109.162	107.906	0.587
		4	113.75	112.626	109.914	1.716
		5	117.142	116.1	111.61	3.362
5	0.5	1	86.17	89.536	86.642	1.9058
		2	93.55	99.142	94.25	2.968
		3	102.776	105.418	99.762	2.621
		4	107.202	112.498	104.236	3.665
		5	117.122	116.254	109.198	4.855
6	0.6	1	87.058	91.516	89.97	2.322
		2	96.626	100.122	95.77	2.231
		3	106.684	103.942	99.46	3.389
		4	108.25	110.27	104.382	2.636
		5	113.048	116.01	111.448	2.402

The coefficient of variation allows comparing statistical series in terms of standard deviation. A lower coefficient of variation indicates better grouping around the average value. Table 2 shows a coefficient of variation smaller than 5.

Data from Table 2 were used to calculate the coefficients of equation (2) using the Mathcad mathematical software. The input data were the values measured for each type of nozzle and working pressure corresponding to the aqueous solution that was tested.

Calculation of k, x and y coefficients was performed by determining the minimum of the function defined by equation (3) using Mathcad. For initialization, the values x= 1; y= 1; k= 1.5 were used.

After the calculations, the values of x, y, k coefficients for the three solutions were obtained, as presented in Table 3.

Table 3

Values of x, y, k coefficients in equation (2) for the three tested solutions

Coefficient name	Solution 1	Solution 2	Solution 3	Correlation coefficient R
x	0.141	0.123	0.158	0.966
y	0.07	0.019	0.012	0.911
k	1.77	1.703	1.545	0.949

Also, in table 3 were inserted the values of the correlation coefficient R for the three cases, by which is evaluated the correctness of the model for estimating the values of α jet angle compared to the measured values. It is found that the values of R ≥ 0.911, which proves a good accuracy obtained by applying the model given by equation (2) using the coefficients in Table 3 for obtaining the jet angle (α).

For example, in the case of **solution 1**, the calculation model used is:

$$\alpha = 1.77\left(\frac{p}{1}\right)^{0.141} \cdot \left(\frac{D}{0.0001}\right)^{-0.07} \text{ (rad)} \tag{4}$$

The two other calculation models for solutions 2 and 3 are obtained in a similar manner.

Thus:

- $$\alpha = 1.703\left(\frac{p}{1}\right)^{0.123} \cdot \left(\frac{D}{0.0001}\right)^{-0.019} \text{ (rad)} \tag{5}$$

for **solution 2**

- $$\alpha = 1.545\left(\frac{p}{1}\right)^{0.581} \cdot \left(\frac{D}{0.0001}\right)^{-0.012} \text{ (rad)} \tag{6}$$

for **solution 3**

in equations (4), (5) and (6), p(bar) and D(m) are replaced).

To strengthen the confirmation of using relations (4), (5) and (6) in the prediction by calculation of the nozzle jet angle values in the three situations analysed, a comparison of the data obtained from the calculation with those obtained from experiments was performed.

Comparative data are shown in Table 4.

Table 4

Data estimated by relations (4), (5) and (6) for angle α(degrees) compared to the values measured and their corresponding relative errors

Nozzle	Nozzle diameter D (mm)	Pressure (bar)	Measured, estimated and relative errors values of α° angle								
			solution 1			solution 2			solution 3		
			α_c(°)	α_m(°)	ε (%)	α_c(°)	α_m(°)	ε (%)	α_c(°)	α_m(°)	ε (%)
1	0.1	1	101.4	104.6	-3.106	97.547	100.546	-2.983	88.496	83.892	5.488
		2	111.8	112.2	-0.338	106.209	100.982	5.176	98.754	96.64	2.188
		3	118.3	117.7	0.564	111.628	106.452	4.862	105.297	106.342	-0.983
		4	123.2	119.4	3.225	115.64	110.59	4.566	110.2	108.316	1.739
		5	127.2	122.0	4.217	118.851	114.468	3.829	114.16	112.524	1.454
2	0.2	1	96.6	99.2	-2.606	96.302	99.788	-3.493	87.741	84.672	3.625
		2	106.5	108.9	-2.225	104.854	111.162	-5.675	97.911	97.502	0.419
		3	112.8	115.8	-2.623	110.204	114.816	-4.017	104.398	108.968 6	-4.194
		4	117.4	118.162	-0.630	114.164	119.016	-4.077	109.26	113.134	-3.424
		5	121.2	120.73	0.359	117.334	120.882	-2.935	113.186	116.576	-2.908
3	0.3	1	93.9	93.722	0.205	95.582	97.898	-2.366	87.302	87.1896	0.129
		2	103.5	104.77	-1.177	104.069	105.17	-1.047	97.422	96.188	1.283
		3	109.6	111.994	-2.124	109.379	110.886	-1.359	103.876	102.77	1.076
		4	114.1	115.68	-1.328	113.31	114.466	-1.010	108.714	109.71	-0.908
		5	117.8	118.788	-0.844	116.456	120.47	-3.332	112.621	115.624	-2.597
4	0.4	1	92.0	93.254	-1.293	95.074	98.298	-3.280	86.993	91.88	-5.319
		2	101.5	102.68	-1.170	103.516	104.634	-1.068	97.076	103.328	-6.051
		3	107.4	108.194	-0.699	108.798	109.162	-0.333	103.508	107.906	-4.076
		4	111.9	113.75	-1.647	112.708	112.626	0.073	108.328	109.914	-1.443
		5	115.4	117.142	-1.448	115.837	116.1	-0.227	112.221	111.61	0.547
5	0.5	1	90.6	86.17	5.172	94.681	89.536	5.746	86.753	86.642	0.128
		2	99.9	93.55	6.801	103.089	99.142	3.981	96.808	94.25	2.714
		3	105.8	102.776	2.922	108.349	105.418	2.780	103.223	99.762	3.469
		4	110.1	107.202	2.749	112.243	112.498	-0.227	108.03	104.236	3.640
		5	113.7	117.122	-2.953	115.36	116.254	-0.769	111.912	109.198	2.485
6	0.6	1	89.5	87.058	2.784	94.362	91.516	3.110	86.558	89.97	-3.792
		2	98.7	96.626	2.095	102.741	100.122	2.616	96.591	95.77	0.857
		3	104.4	106.684	-2.102	107.984	103.942	3.889	102.99	99.46	3.549
		4	108.8	108.25	0.468	111.865	110.27	1.446	107.786	104.382	3.261
		5	112.2	113.048	-0.726	114.971	116.01	-0.896	111.66	111.448	0.190

Observation:

The following notations were made:

- α_c – *the value of the jet angle calculated with the corresponding relation*
- α_m – *measured jet angle value*
- $\varepsilon = \frac{\alpha_c - \alpha_m}{\alpha_m} * 100$, *relative error*

Following the data in the table, one can notice that out of the 29 values for each of the three solutions, 90.8% of the values of relative error calculated compared to the measured ones do not exceed the limits of ± 5%.

On the basis of these observations it is found that the data obtained by applying relations (4), (5) and (6) can be used with good results in calculating the values of the nozzle jet angles, values that are useful in the engineering activities of design and use in practice of spraying machines.

4. Conclusions

In this paper were conducted experimental determinations on nozzle jet angle under controlled conditions for different nozzles, working pressures and solutions with different physical properties (density, viscosity and surface tension). The research was realized in order to demonstrate that the nozzle jet angle has variable values depending on the working conditions, thus providing also variable coverage degrees for the spraying work.

Tests on the three aqueous solutions reveals that the size of the jet angle is insignificantly influenced by the physical properties of the solutions when they have values in the ranges similar to those specified.

The theoretical model proposed by authors in a previous paper [13], the type of equation (2) for estimating the nozzle jet angle, shows its dependence on working pressure, nozzle diameter and physical properties of the spraying solution.

The results from the tests were subsequently used in the numerical calculation of the theoretical model coefficients expressed by the equation of form (2) and presented in Table 3. Thus, the concrete relations (4), (5) and (6) were proposed for estimating the angle α of the jet for each of the researched solutions.

The results obtained revealed a strong correlation between the experimental data and the values calculated for each aqueous solution studied, obtaining a correlation coefficient R in the range 0.91 - 0.97.

Thus, three efficient mathematical models for calculating the nozzle jet angle were obtained. By analysing the results calculated using these models, it is observed that 90.8% of the relative error values for the calculated values compared to the measured ones were within the limits of ± 5%, which proves the utility and applicability of relations (4), (5) and (6).

It can be concluded that the variation of the nozzle jet angle, depending on the working pressure for the measured values and the calculated ones, does not differ significantly, which shows that the proposed mathematical model can be successfully used in practice. The physical properties of the solutions used influence the nozzle jet angle values on a small scale value.

The obtained mathematical models are useful in engineering activities in the field of designing and efficient use of spraying machines. One could use the models to accurately predict the coverage degree obtained by its spraying machine in function of the chosen nozzles, the distance between them and the imposed working height.

R E F E R E N C E S

[1] *Stahli W., Bungescu S.*, Machines for applying phytosanitary treatments and foliar fertilization of vegetable crops, Agroprint USAMVBT Timisoara Publishing House, 2003
[2] *Hilz E., Vermeer A. W.P.*, Spray drift review: The extent to which a formulation can contribute to spray, drift reduction, Crop Protection 44, pp.75-83, 2013
[3] *Bran M.*, Comparative agricultural technologies: guidance for practical works, ASE Bucharest Publishing House, 2009
[4] *Boja F. C.*, Research on technological limits for the use of man-made devices in combating pests in forest nurseries, doctoral thesis abstract, Brasov, 2010
[5] *Stahli W., Bungescu S.*, Apparatus, equipment and machinery for plant protection, AGROPRINT USAMVBT Timisoara Publishing House, 2006
[6] *Ballester J., Dopazo C.*, Discharge coefficient and spray angle measurements for small pressure-swirl nozzles, Atomization and Sprays, vol. 4, pp. 351-367, 1994
[7] *Heidary Al M., Douzals J.P., Sinfort C., Vallet A.*, Influence of spray characteristics on potential spray drift of field crop sprayers: A literature review, Crop Protection 63, pp.120÷130, 2014
[8] *Foque D., Pieters G.J., Nuyttens D.*, Spray deposition and distribution in a bay laurel crop as affected by nozzle type, air assistance and spray direction when using vertical spray booms, Crop Protection, vol. 41, pp. 77-87, 2012
[9] *Lemneanu N. , Cristea E., Jianu C.*, Combustion plants with liquid fuels, Technical Publishing House, Bucharest, 1986
[10] *Staicu C. I.*, General dimensional analyse, Technical Publishing House, Bucharest, 1976.
[11] *Mihăiţă A.*, Better efficiency of phytosanitary treatments in fruit-growing agro-systems, Doctoral thesis, USAMV Bucharest, 2003
[12] *Krasnicenko A. V.*, Farm Machinery Builder Manual Manufacturer of Agricultural Machine, vol. 2, Technical Publishing House, Bucharest, 1964
[13] *Roşu (Niţu) M., Matache M., Vlăduţ V., Căsăndroiu T., Bungescu S.*, Influence of the jet's angle size on the spraying process, Proceedings of The 43 International Symposium on Agricultural Engineering "Actual Tasks on Agricultural Engineering", pg. 275-286, 2015, ISSN 1333-2651, Opatija – Croatia
[14] *Roşu (Niţu) M., Manea D., Cujbescu D.*, Comparative analysis of distribution uniformity in application of phyto-sanitary treatments in field crops at different pressures, INTERNATIONAL SYMPOSIUM ISB-INMA TEH, 2013
[15] *** Catalogue Lechler, Agricultural Spray Nozzle and Accessories, 2016 (http://www.lechler.de)