INFLUENCE OF THE SPRAYING PRESSURE AND NOZZLE DESIGN ON SPRAY DISINTEGRATION

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Summary

The design of a sprayer nozzle used for chemical plant protection should fulfill technical, efficiency, and environmental demands. The level of meeting these demands as well as their optimizing can be best evaluated by gathering information during the machine operation. This paper analyses functional accuracy concerning spray coverage of upper and lower leaf surfaces in case of use of different nozzle designs operating at varied working pressures. The research was conducted at the following spraying pressures: 0.1, 0.2, 0.3, 0.4, and 0.5 MPa for three TeeJet nozzle designs, which are TeeJet 11002, 11004, and 11006. The average coverage in percentage terms and the average droplet density of the droplet impact on upper and lower sides of wheat leaves are determined. The quality of the disintegrated spray deposition is established by assessing droplet impacts on water sensitive paper. The best average upper leaf side coverage is achieved by a TeeJet 11006 nozzle (27.247%) and somewhat weaker results are achieved by a TeeJet 11004 nozzle (24.755%) and a TeeJet nozzle 11002 (22.355%). The average coverage of upper leaf sides is insufficient since the spray is present only in traces. In case when spray is applied by TeeJet 11006 nozzles the achieved coverage of upper leaf sides is 6.392%. A TeeJet 11004 nozzle achieved the coverage of 3.629%, and the weakest result by far is achieved by TeeJet 11002 nozzle (0.27%). Higher spraying pressures usually result in a better upper and lower wheat leaf sides coverage, and at the same time it produces a higher level of droplet disintegration, which is not the case for TeeJet 11002 and 11004 but for upper leaf sides. The results of a derived regression analysis show the presence of a square dependence between the spraying pressure and area impact density on a leaf as well as a dependence of pressure and leaf coverage for all the aforementioned nozzle types.

Key words: spraying pressure, nozzle, spray, disintegration, droplet, coverage, surface density, sprayer

1. INTRODUCTION

Plant protection machines apply chemicals over plants or surface or into soil. They include various kinds of sprayers, atomizers, mist sprayers, pulverizers, and machines that apply pesticides into soil.

Sprayers are machines used for chemical plant protection, which pump the pesticide droplets and discharge them under pressure in a jet form over a target area.

The main task of a sprayer is to disperse the liquid jet into droplets of a specific size, and to spread them uniformly across the target area, Eichorn [1]. The disintegrated droplets, which are a result of pressurized atomisation, get dispersed, and due to the surface contact they deposit onto the surface. The geometrical form of the surface changes, i.e. the droplet form changes from a sphere into a spherical calotte. The calotte occupies a significantly bigger area compared to a sphere, which means that the coverage of a target area is significantly better. A coverage level depends on the tension area, droplet viscosity, area quality assessment, area inclination, droplet spectre, and similar, Maceljski [2]. Droplet deposition speed onto the target area is an important factor for spray application efficiency assessment (pesticide dissolved in water). The following formula is used for calculation of the droplet deposition speed and it is a result of the following analysis (Figure 1.).

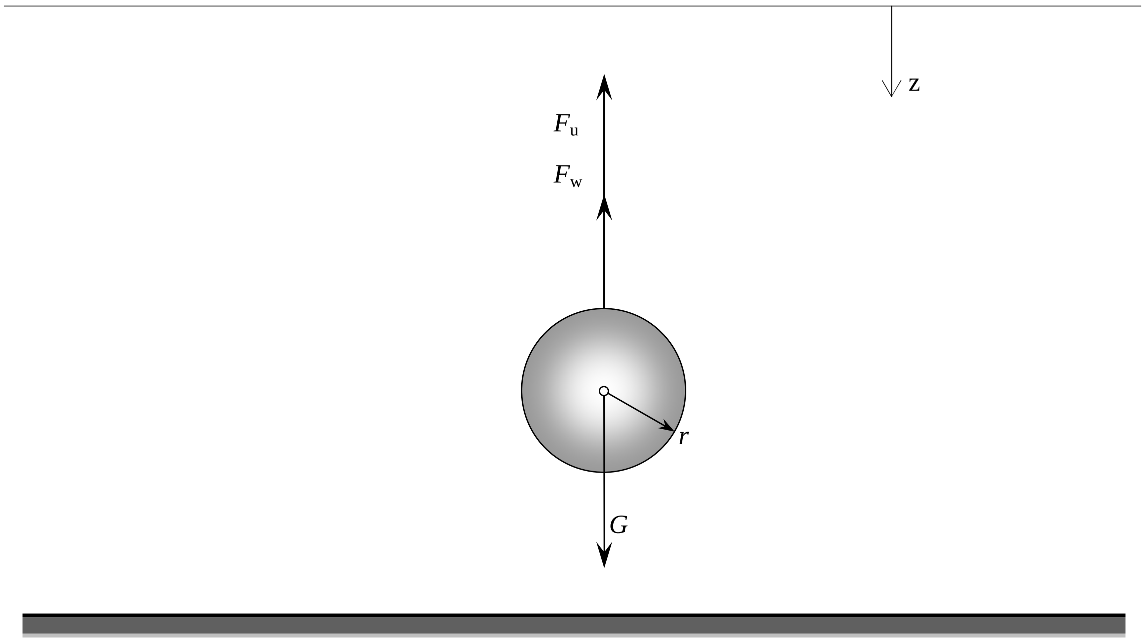

Figure 1. Spray droplet as a spherical model and forces acting upon it

A spray droplet as a spherical model falls through the air due to the action of mass G. The downward movement of the drop is opposed by lift force Fu and air resistance force Fw. In the beginning, the mass is bigger than both lift force and air resistance, so that the drop moves downwards with acceleration. As the drop speed increases resistance force increases as well, and after a certain time both lift and resistance forces become equal to the drop mass. The result of this is a constant droplet speed from now on. The constant speed can be computed on the base of the forces equilibrium acting on the droplet.

$$G = F_u + F_w \tag{1}$$

or

$$mg = m_z g + 6\pi \eta r v \tag{2}$$

i.e.

$$\frac{4}{3} r^3 \pi \rho g = \frac{4}{3} r^3 \pi \rho_z g + 6\pi \eta r v \tag{3}$$

and after the final arrangement

$$v = \frac{2}{9} \frac{r^2 g}{\eta} (\rho - \rho_z) \tag{4}$$

v – droplet speed ms^{-1}
r- droplet diameter m
g- Earth acceleration ms^{-2}
η – fluid (spray) dynamic viscosity coefficient Pa·s
ρ – spray density in kgm^{-3}
ρ_z – air density in kgm^{-3}

George Stokes, an Irish mathematician and physicist defined a formula for force resistance which is $F_w=6\pi\eta rv$ based on the assumption that a sphere moves at a low speed in viscous fluid. The mean coefficient value for dynamic spray viscosity at a normal atmospheric pressure of 1,013 hPa and air temperature of 20º C is 0,00172 Pa·s, Landau, L.D. and Lifshitz, E. M. [3]. It is obvious from the formula (4) that the movement speed of disintegrated droplets is in proportion with the mean coefficient value. A smaller diameter implies a smaller speed and a bigger danger of missing the target, i.e. an undesirable deposition. Spray disintegration is under the influence of the nozzle orifice as well as the pressure level, Šumanovac et al. [4]. Higher pressure disintegrates drops more strongly. The disintegration (dispersion) is stronger at the initially lower spraying pressures. Jets with smaller droplet spectre cover the target area significantly better than bigger droplet jets. The most favourable drop size applied to in plant protection is 100-500 µm, Tuck C. R. et al. [5], which is due to the fact that smaller drops are inclined to evaporation and drift, whereas bigger ones drip off from target plants causing soil and underground water pollution. Due to these the efficiency of chemical plant protection is decreased. In the case of pesticide application whose carrier is water it covers two or three times a bigger area because droplets changes their form from a sphere into a calotte. If oil is used as a carrier this change is even bigger and it covers a ten to fifteen times bigger area. The droplet diameter at the nozzle outlet is in this case bigger than 150µm, Miller, P. C. H. and Hadfield, D. J. [6]. An average diameter of a droplet within a disintegrated spray jet spectre can be expressed in three ways:

$$d/a = \frac{\sum nd}{\sum n} \tag{5}$$

The arithmetic mean diameter (NMD – number median diameter) is calculated by the addition of the diameters of all droplets. The total sum is further divided by the total droplet number:

d/a –arithmetic mean diameter of a droplet in ηm
n – number of droplets
d –drop diameter in µm

The diameter expressed in this way does not show any important jet characteristic, and in accordance to that fact is only rarely used, Bošnjaković [7].
The other diameter used to define a droplet size is the volume median diameter (VMD – volume median diameter), which expresses the size of the drop that splits the overall volume of discharged drops into two equal parts. Knowing this diameter you can calculate the droplet number in a certain liquid quantity as well as the density (number) of the droplets on an area.

$$d/V = \sqrt[3]{\frac{\sum nd^3}{\sum n}} \tag{6}$$

d/V – droplet *volume* diameter µm
n – droplet number
d – droplet diameter µm

The third diameter, which defines the droplet size, is the surface median diameter (SMD – surface median diameter). It represents the diameter of the drop whose volume and surface proportion is the same for the whole liquid quantity. This diameter allows calculating the target area droplet coverage.

$$d/VP = \frac{\sum nd^3}{\sum nd^2} \tag{7}$$

d/VP –volume surface mean droplet diameter µm
n – number of droplets
d – droplet diameter µm

Pesticide amount is adjusted in sprayers in order to avoid insufficiency or excess. They can cause a decreased efficiency level and phytotoxic effects as well as inappropriate pesticide consumption. The level of liquid jet disintegration is highly dependent on the spraying device, Šumanovac et al. [8]. One of the most important parts of a sprayer is a nozzle. They use hydraulic pressure to for liquid dispersal. Further, they form a jet and take care of the range and amount of discharged spray. Today in use you can most often find whirl nozzles (they form a cone jet), TeeJet nozzles, slot nozzles (they form a trapeze jet), and fan nozzles (they form an irregular fan jet), Srivastava, A. K. et al [9]. Technical characteristics of a nozzle depend on its design and kind. The design influences the jet form and maximum distance covered, the drop spectre and the machine capacity. Every nozzle type produces a jet of certain characteristics under certain circumstances, Ganzelmeier H. [10]. Next to the above-mentioned nozzle types the following nozzle types are also used but under specific conditions and in a limited number: rotating, rain drop, hydropneumatic, electrostatic, and vibrating nozzles. The researches are conducted on the standard TeeJet nozzle (Fig. 2.a and 2.b.). It consists of a body, filter, inlet (a plate with a slot) and a nut. The filter is made of copper alloy or synthetic materials with slots or a net made of metal or synthetic threads. The filter can have a ball-shaped valve with a spring that closes the nozzle outlet after the end of the operation in order to avoid spray dripping. The filter net density should match the outlet dimensions. The density is expressed as a number of threads per inch length. The sign 50 Mesh, for example, means that the filter has 50

threads along the length of 25,4 mm. The plate is made of stainless steel, resistant copper alloys, ceramics or special synthetic materials. The nozzle outlet is in the form of an elongated ellipse (elongated slot). Its depth is 3-4 mm, and it produces a fan-shaped jet of an angle of 65º to 120º. The nut on a nozzle is used for fixing the inlet (plate) with the outlet and the body or a nozzle carrier. It is made either of metal or synthetic material. The main task of a nozzle is to cover upper and under sides of leaves in a satisfactory way, Sebastijanović et al. [11].
High yield wheat sorts require an intensive disease, pest, and weed control. If not, they can seriously harm the expected yield, Šumanovac [12]. The aforementioned protective actions should be performed during the whole vegetation period, which implies an intensive use of agricultural machinery, in the first place of tractor sprayers Šumanovac [13]. The research aims to analyse the coverage and number of droplets (impacts) per an area unit of a wheat leaf related to the pressure change for three different nozzle types. Further, to recommend certain technical solutions, which can improve the spray application level, environmental protection, and the efficiency of agricultural production.

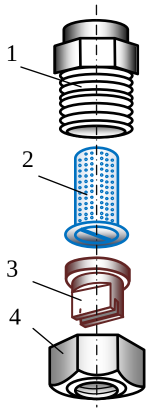

Fig. 2. a) Main parts of a TeeJet nozzle
1. Body, 2. Filter,
3. TeeJet nozzle inlet, 4. Nut

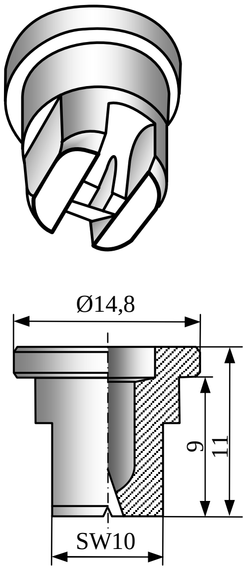

Fig. 2. b) TeeJet nozzle inlet

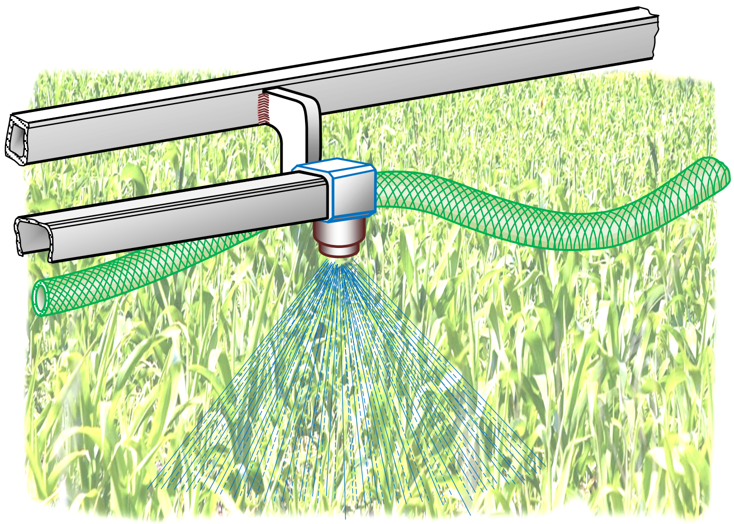

Fig. 2. TeeJet nozzle in operation

2. OPERATING MODELS

The protection of winter wheat (*Triticum aestivum* L.) from plant diseases is performed by a RAU-2000 sprayer on the fields of Mednik Company in Županja, Eastern Slavonia, the Republic of Croatia. Alto Combi 42 preparation is used. 0.5 lha^{-1} is mixed with 200 $lha^{-1}$of water. The research is performed for the following spraying pressures: 0.1; 0.2; 0.3; 0.4; and 0.5 MPa in relation with the three TeeJet nozzle types (11002, 11004,11006) during wheat spike formation. The operating angle of a nozzle is 110° (according to the label 11002 the underlined number); the flow is 0.76 $lmin^{-1}$, which equals 0.2 US gal min^{-1} (according to the label 11002 the underlined number). European manufacturers use similar labels but for flow which is marked in litres per minute ($lmin^{-1}$). The experiment is performed at an air temperature of 26°C in semi-cloudy windless weather. The spraying speed is 6-7 kmh^{-1}. Water sensitive paper is used to assess the spray deposition quality. The papers are set apart at a meter's distance transversally to the sprayer. They are at 60-70 cm above the ground. The average height of wheat is 85 cm. Five papers are set horizontally on the upper and lower leaf sides for each repetition of the experiment. The papers are fastened to the wheat leaves by paper clips.

Fig. 3. The position of a water-sensitive paper in wheat crops

The collected data are processed by an image analyser *OPTOMAX Vs* equipped by appropriate measuring devices at the Institute for Hop Growing in Žalec, the Republic of Slovenia An average coverage (%) as well as average area impact density are assessed (lcm^{-2}) both for the upper and lower leaf sides of the SANA winter wheat sort. Based on technical reasons no analysis is performed in relation with the water-sensitive papers used for the assessment of the performance of a sprayer operating at 0.5 MPa and applying TeeJet 11004 nozzles as well as TeeJet 11006 nozzles. Namely, experimental papers were inundated so that it was not possible to determine either the coverage or surface density).

The choice of the regression equation among the five possible ones (linear, square, potential, logarithmic, and exponential) is based on the biggest value of coefficients of correlation among the observed features. A determination coefficient (R^2) represents the interpretation of the influence exerted by an independent value to a dependent one and is usually expressed as a percentage (%). The alienation coefficient ($l-R^2$) expresses the remaining effects due to the influence of some unknown factors. It is also expressed as a percentage.

3. REASERCH RESULTS

In Tables 1. and 2. you can find the gathered and processed data; $\overline{X}$ represents the arithmetic mean value, σ_x is a standard deviation and *C.v.* (%) represents a variability coefficient. An analysis of the leaf coverage shows a very high variability in case when TeeJet 11002 nozzle is used at different spraying pressures. The coverage level ranges from 12.008% at 0.1MPa to 43.566% at 0.5 MPa.

The variability of the area density of droplet impacts (cm^{-2}) is significantly smaller and ranges from 46.842% at the spraying pressure of 0.2 MPa to 71.082% at 0.4 MPa. The lower leaf side coverage is insignificant. It ranges from 0.121% to 0.400% for TeeJet 11002 nozzle. On the other side the area density of droplet impacts is very variable (cm^{-2}). At the same time a higher level of droplet disintegration is achieved during spray application by TeeJet 11006 nozzles, which is not the case for TeeJet 11002 and TeeJet 11004. The last refers to the lower leaf side. TeeJet 11004 and TeeJet11006 performed a significantly better upper leaf spray coverage than a lower leaf coverage, which proves to be true especially when the spraying pressure is increased. It results in a better disintegration of droplets, which means that they are smaller and based on that fact they leave an increased number of traces per a square centimetre. This finally results in proportional improvement wheat leaf coverage.

TeeJet 11006 achieves the best coverage on average during spray application, and it reaches 27.247% for the upper leaf side and 6.392% for the lower leaf side. Somewhat weaker results are achieved by TeeJet 11004 nozzle. In this case the coverage of the upper leaf side is 24.755%. TeeJet 11002 achieves the weakest results and the coverage is 22.355%. The coverage of the upper leaf side ranges within the limits of 2.759% at 0.1MPa (TeeJet 11006) to 43.566% at 0.5 MPa (TeeJet 11002). The upper leaf coverage is unsatisfactory since it ranges from only 0.121% at 0.5 MPa (TeeJet 11002) to 21.258% at 0.4 MPa (TeeJet 11006). The research results are shown in Tables 1. and 2. and in histogram charts (Figure 4., 5., and 6.)

Table 1. Average coverage of the upper and lower surface of a winter wheat leaf in dependence on the nozzle type and spraying pressure

Pressure/ MPa	Nozzle type					
	TeeJet 11002		**TeeJet 11004**		**TeeJet 11006**	
	Leaf surface coverage %					
	Upper	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**
0.1	12.008	0.216	9.178	14.167	2.759	1.492
0.2	16.712	0.140	31.284	0.164	29.219	0.296
0.3	22.839	0.400	23.425	0.104	35.289	2.524
0.4	16.652	0.486	35.134	0.080	41.722	21.258
0.5	43.566	0.121	-	-	-	-
$\overline{X}$	22.355	0.272	24.755	3.629	27.247	6.392
σ_x	12.465	0.162	11.471	7.026	17.105	9.952
C.v. %	55.759	59.559	46.338	193.607	62.777	155.694

Table 2. *Average area impact density on a winter wheat leaf in dependence on the nozzle type and spraying pressure*

Pressure/ MPa	Nozzle type					
	TeeJet 11002		**TeeJet 11004**		**TeeJet 11006**	
	Area impact density on the leaf surface cm^{-2}					
	Upper	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**
0.1	49.837	2.351	17.439	21.972	6.301	11.611
0.2	46.842	1.943	43.168	28.949	35.148	4.603
0.3	47.234	20.786	40.262	0.716	47.292	13.605
0.4	71.082	18.106	46.703	0.716	67.963	31.772
0.5	47.947	49.840	-	-	-	-
$\overline{X}$	52.588	18.605	36.893	13.088	39.176	15.398
σ_X	10.402	19.509	13.234	14.567	25.765	11.579
C.v. (%)	19.780	104.86	35.871	111.300	65.767	75.198

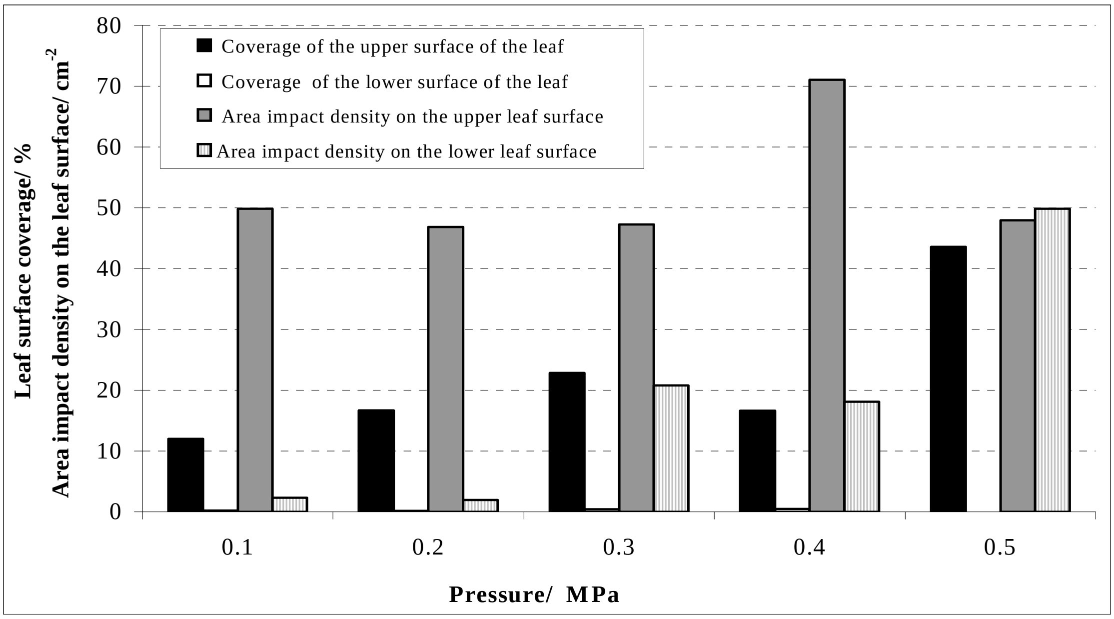

Fig. 4. Average coverage and area impact density on the upper and lower winter wheat leaf sides in case of the use of TeeJet 11002

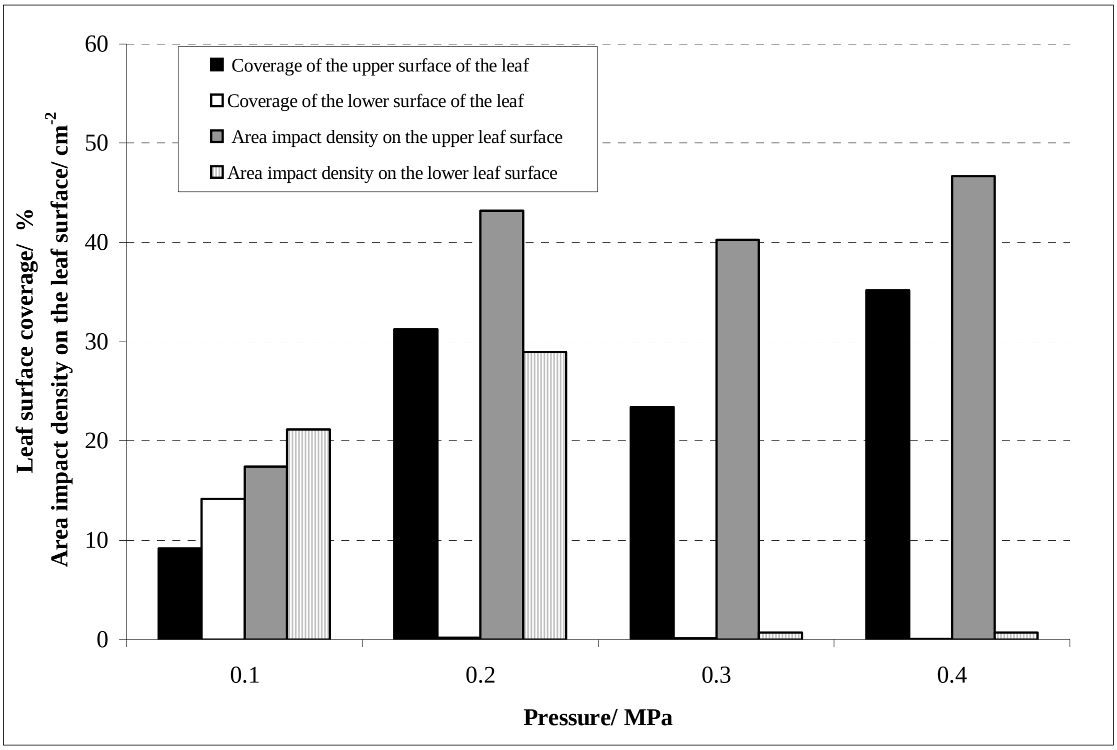

Fig. 5: Average coverage and area impact density on the upper and lower winter wheat leaf sides in case of the use of TeeJet 11004

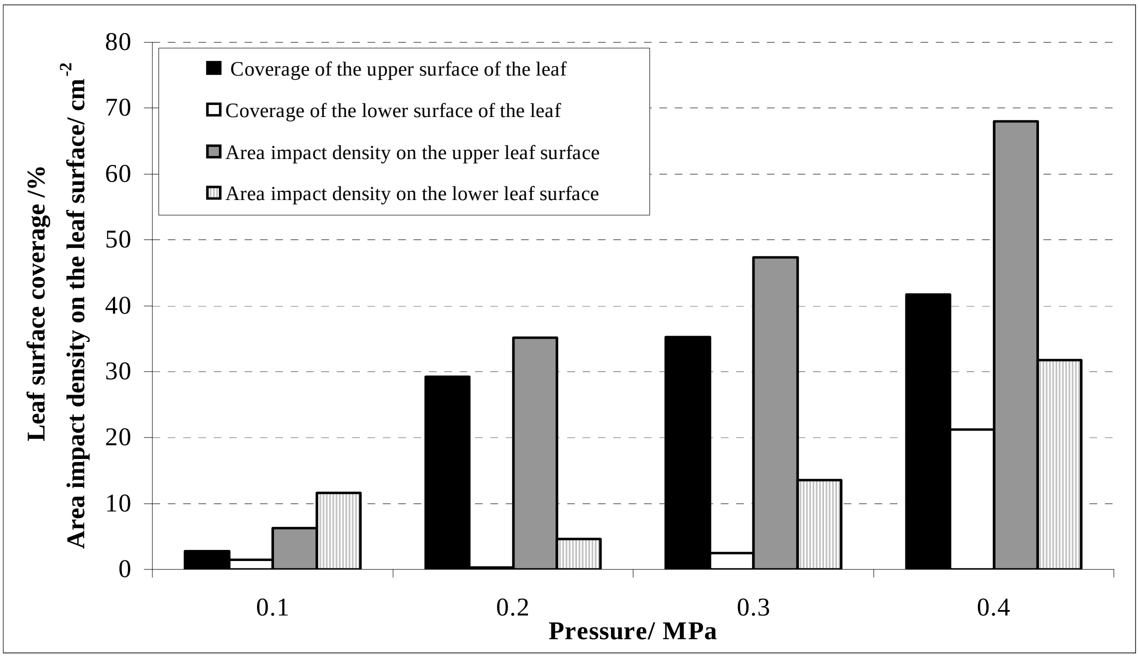

Fig. 6. Average coverage and area impact density on the upper and lower winter wheat leaf sides in case of the use of TeeJet 11006

4. REGRESSION ANALYSIS

4.1. The influence of a spraying pressure and nozzle type on the pesticide coverage of winter wheat leaf surfaces

The results of the regression analysis show the presence of a square form of dependence between the spraying pressures and upper wheat leaf coverage for the nozzle types of TeeJet 11002 and 11006. Here you can find the TeeJet 11002 dependence regression equation in a square form:

$$y = 229.33x^2 - 74.541x + 19.492 \quad (8)$$

The correlation coefficient is R=0.871.

The TeeJet 11006 dependence is defined by the following equation:

$$y = -500\text{-}75\ x^2 + 373.34\ - 28.533 \quad (9)$$

The correlation coefficient is very high R=0.987.

Square form equations define spray coverage of the lower leaf sides for all the three nozzles:

- TeeJet 11002:
  $$y = -5\text{-}3714\ x^2 + 3\text{-}3789x - 0.1502 \quad (10)$$
  The correlation coefficient is R=0.637.
- TeeJet 11004:
  $$y = 349.48\text{-}217.06x + 31.683 \quad (11)$$
  The correlation coefficient is R=-0.967.
- TeeJet 11006:
  $$y = 498.25x^2 - 187.6x + 15.923 \quad (12)$$
  The correlation coefficient is R=0.985.

A potential equation $y=83.229\ x^{0.8808}$ (13) defines the influence of the spraying pressure level on the upper wheat leaf coverage in case when TeeJet 11004 is used. The correlation coefficient is R=0.870.

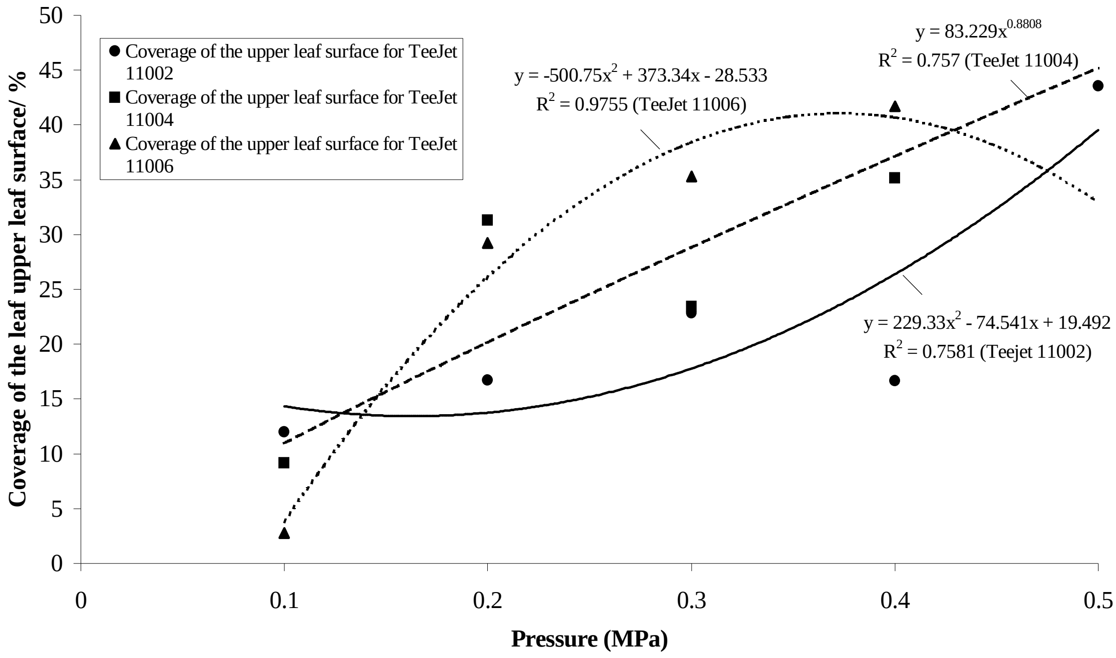

Fig. 7. Coverage of the upper leaf surface for three nozzle types depending on the spraying pressure

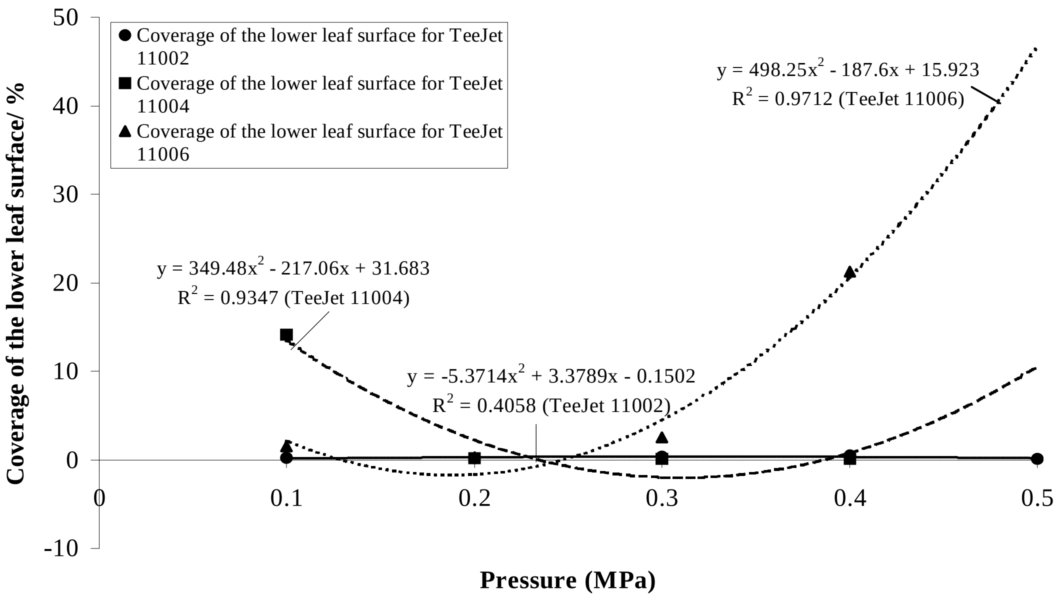

Fig. 8. Coverage of the lower leaf surface for three nozzle types depending on the spraying pressure

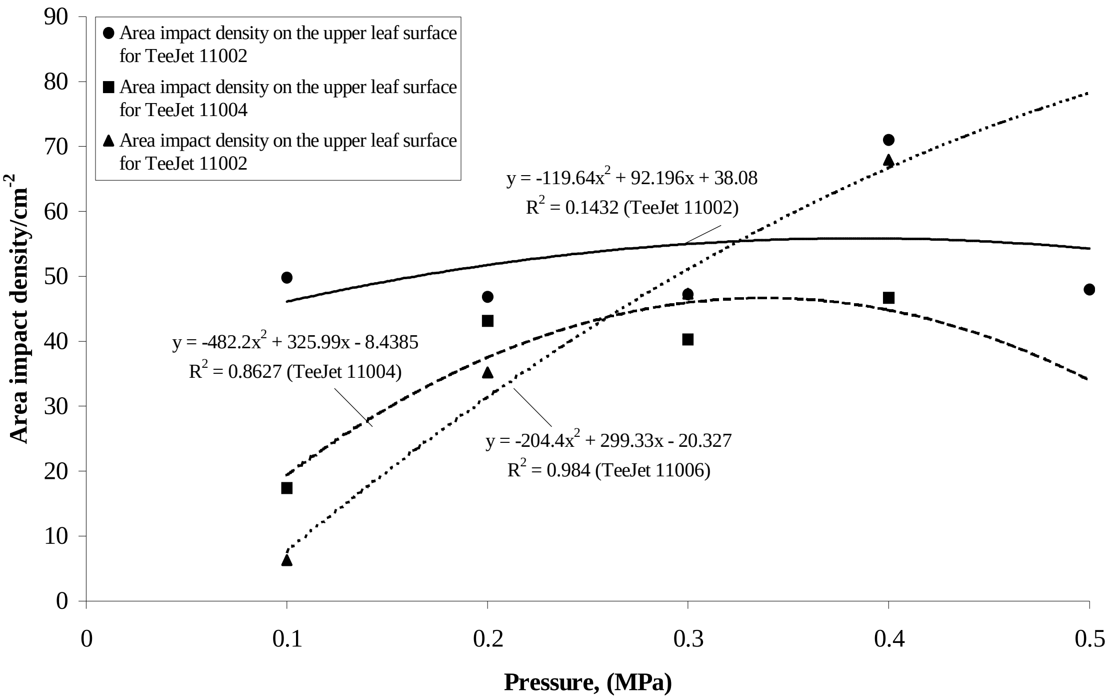

Fig. 9. Area impact density on the upper leaf surface for three nozzle types depending on the spraying pressure

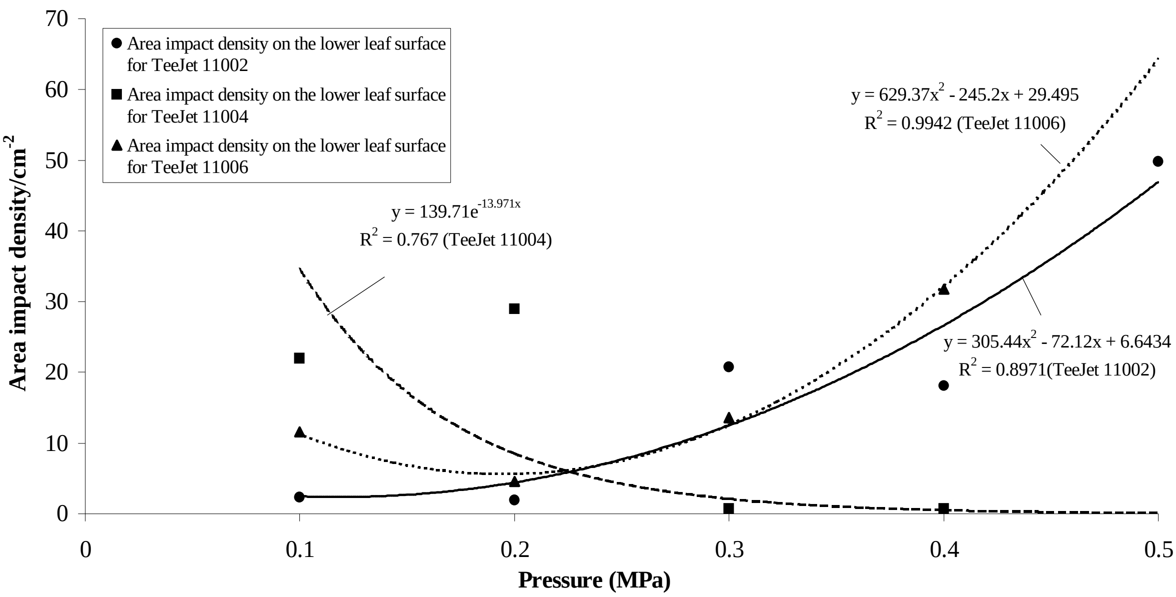

Fig. 10. Area impact density on the lower leaf surface for three nozzle types depending on the spraying pressure

5. CONCLUSION

The obtained results concerning the spray deposition quality applied by a RAU-2000 sprayer at the present pressure levels are satisfactory as far as the upper leaf surface and on the assumption that a constant operating speed of 6-7 kmh^{-1} is maintained. The achieved coverage for TeeJet 11006 ranges from 2.759% at the spraying pressure of 0.1 MPa to 43.566% at 0.5 MPa for TeeJet 11002 nozzle. The upper leaf coverage at the spraying pressure of 0.4 MPa is significantly lower than expected. This should be paid special attention to in future researches in order to give the reasons for this difference. Pesticide deposition on both leaf sides at all researched pressures and for all types of nozzles is insufficient, which is of great importance for the control of plant diseases. In most cases a disease occurs on lower leaf surfaces, but a disintegrated spray is hardly applied to this side of a leaf, which decreases the phytotherapeutical effect and results in an unsatisfactory protection level. An improved level of droplet disintegration and leaf coverage could be achieved by the incorporation of a jet disintegration hydropneumatic device (Sleeve Boom, Twin Sprayer, Tehnostroj, RAU-Air Plus), which affects the liquid jet from nozzles by a strong airflow. In this way it disintegrates the jet in a better way, and due to air turbulences and reflections the lower leaves get also covered with spray. The wheat leaf coverage ranges from 80-100% for the upper leaf side and 60-80% for the lower leaf side in case of use of the aforementioned devices. The coverage is better and the wind drift is lower since the droplets are an integral part of the plant mass. In this way less spray is used and there is no unnecessary environmental pollution.

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