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Design of the Optimized and Downsized Axial Fan for the Air Carrier Orchard Sprayers

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Abstract

The new vineyard and orchard installations are made with a high intensity of plants per hectare and therefore with a reduced distance between the rows. The tractors and the air carrier sprayers for plant protection, must therefore have smaller width.
In consequence, a method of design of axial fans for the air carrier sprayer, to get a small diameter without losing the performance required by the agrochemical applications, must also be studied. The new method was found by imposing a law of Compound Vortex for the tangential component of absolute air speed. In consequence the equations for: the axial component of the absolute air velocity, the flow rate, the total specific energy and the invariance of the lift coefficient versus the radius, were found. Then, the method consists in the solution of the system of these four equations to determine the fan design parameters. This new method allows to obtain a reduction of the external diameter of the fan by a factor of 0.8 and a reduction of the lift coefficient because imposed constant vs. the radius. Therefore the new method may allow to further increase the total specific energy. Finally, there was no significant difference between the average speed, relative to airfoils, of the new method (Compound Vortex) and of the traditional method one (Free Vortex) and then there are no downgrades in the fluid dynamic efficiency.

Keywords: Axial fan, Air sprayer, Design, Agricultural engineering, Mathematical modeling

1. Introduction

In crop protection of orchards and vineyards, the air carrier orchard sprayers are widely used. It is mainly characterized by a water-chemical mixture atomization using pressure nozzles and by a transport of the droplets by means of an air jet, produced by an axial fan [1].

In recent years, new orchards and vineyards with a high intensity of plants per hectare, are widely planted. In this manner, lower rows are possible, but also a smaller inter-row distance, with respect to the old less intensive plantation, is present.
This has forced manufacturers of tractors and air carrier sprayers to reduce the width of the machines.

Therefore, also for the axial fans installed in the air carrier sprayers, it would be very useful that they were of reduced diameter, while maintaining the fluid-dynamic performance required by the plant protection treatments. This problem results in a fluid dynamic optimization of the fan [2], and then in the search for a new design method. This is the aim of this work, which begins with the brief description of the traditional calculation method, based on the law of Free Vortex, highlighting the advantage of simplicity and the disadvantage of the highly variable lift coefficient along the blade. So, in this work, a fluid dynamic study of the axial fan for the orchard sprayers [3, 4, 5 and 6], based on an appropriate law of Compound Vortex addressed to achieve a high and constant lift coefficient over the entire blade and, hence a reduced impeller diameter maintaining high fluid dynamic performance and reduced drift [7], will be processed.

2. Fluid dynamics of axial fan

The axial fans adopted in the orchard sprayers are with intubated impeller, mostly without any static blades upstream. The air, produced by the impeller, strikes a plate (Fig. 1) which, placed in the queue to the reservoir, allows the deviation of the flow in the radial direction. This geometrical configuration highlights that the presence of the impact plate also performs the function of the diffuser, i.e. recovery at the pressure energy.

From this observation it was considered that, using at the same time, an appropriate arrangement in the design of the impeller, the stator blades downstream of the impeller are not necessary, but they are instead mounted by some manufacturers of sprayers.

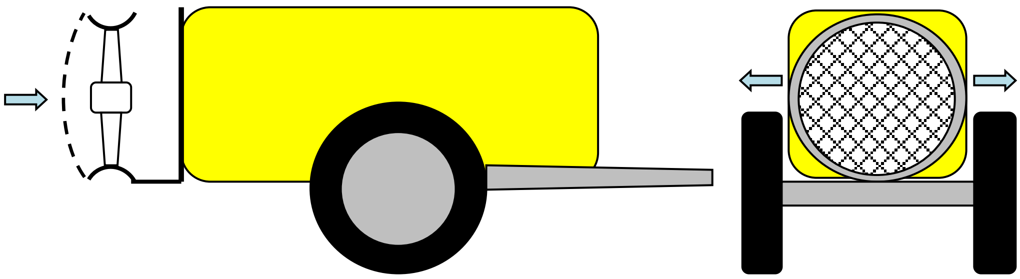

Fig. 1 – Air carrier sprayer for orchard and vineyard protection.

In the design of the impeller, above-mentioned arrangement consists of imposing a total constant pressure (static pressure + dynamic pressure) throughout the field of the absolute flow downstream of the impeller, both in the tangential direction than in the radial one. To understand how to do it, it is necessary to recall some of the fluid dynamics of turbomachinery.
If it is assumed the incompressible fluid, with a minimum error with a limited increase of static pressure that the axial fans produce, the equations of motion of the air (Euler equations), with reference to the absolute flow and to a cylindrical coordinate system, can be written as follows [4]:

$$\frac{1}{\rho}\frac{\partial p}{\partial r} = c_r \frac{\partial c_r}{\partial r} + \frac{c_u}{r}\frac{\partial c_r}{\partial u} + c_x \frac{\partial c_r}{\partial x} - \frac{c_u^2}{r} \tag{1}$$

$$\frac{1}{\rho}\frac{\partial p}{r\partial u} = c_r \frac{\partial c_u}{\partial r} + \frac{c_u}{r}\frac{\partial c_u}{\partial u} + c_x \frac{\partial c_u}{\partial x} + \frac{c_r c_u}{r} \tag{2}$$

$$\frac{1}{\rho}\frac{\partial p}{\partial x} = c_r \frac{\partial c_x}{\partial r} + \frac{c_u}{r}\frac{\partial c_x}{\partial u} + c_x \frac{\partial c_x}{\partial x} \tag{3}$$

where p is the static pressure, c_r is the radial component of the absolute velocity, c_u is the tangential component and c_x the axial one (x is the direction of the axis of rotation of the impeller).
As can be seen, the friction forces have been neglected, so that the equations (1), (2) and (3) express the balance of the inertia forces and the pressure forces, acting on the particles of air. They describe the absolute flow downstream of the impeller. Furthermore, the same equations apply also to the upstream side of the impeller.
Their closed-form solution is, however, allowed only conceding two simplifying assumptions. The first hypothesis consists in considering that the number of the impeller blades is enough high, so that the absolute flow may be considered axial-symmetric with good approximation. It is therefore possible to neglect the derivatives with respect to the variable u. With the latter, the c_r radial component is considered null, namely, that the so-called flow surfaces become cylindrical. All this leads to the following notation, obtained by starting from (1):

$$\frac{1}{\rho}\frac{dp}{dr} = -\frac{c_u^2}{r} \tag{4}$$

If p_0 is called the total pressure, which becomes total energy if the potential energy is neglected, p_0 is well defined:

$$p_0 = p + \frac{1}{2}\rho\cdot\left(c_u^2 + c_x^2\right) \tag{5}$$

and then differentiating with respect to *r* and recalling (4), we obtain:

$$\frac{1}{\rho}\frac{dp_0}{dr} = \frac{c_u^2}{r} + c_u\frac{dc_u}{dr} + c_x\frac{dc_x}{dr} \tag{6}$$

Previously it was talked about the invariance of this total energy p_0, as the condition of optimization for the matching between the fan and the impact diffuser. This is true in the tangential direction, having admitted the axial-symmetric flow, but the invariance of p_0 in the radial direction requires to impose null the left side of (6). So the (6) becomes:

$$\frac{1}{r^2}\frac{d}{dr}\left(rc_u\right)^2 + \frac{d}{dr}\left(c_x^2\right) = 0 \tag{7}$$

Then the equation (7) makes the total specific energy in downstream of the impeller, constant.
But it can also be applied upstream of the impeller, where stator blades that can produce pre-rotation cu of absolute current, do not exist. So with c_u=0, the (7) provides c_x=*constant*.
Returning to the application of (7) downstream of the impeller, a non-null value of the tangential component of velocity c_u downstream must be admited, otherwise the impeller does not transfer pressure energy to the air as will be seen below (2.2). Therefore it is necessary to impose this c_u according to a certain law of variation along the radius *r*. The law of variation of c_u adopted by manufacturers of axial fans for the air carrier sprayer, but not only for them, is the free vortex law, ie:

$$r\cdot c_u = constant \tag{8}$$

So, downstream of the impeller, to obtain the constant total energy of air, the eq. (7) provides:

$$c_x = constant \tag{9}$$

In addition to the equation (7), the continuity equation must also be added, where *Q* is the volumetric flow rate (m^3/s):

$$\frac{dQ}{dx} = 0 \tag{10}$$

The equation (7) states that the flow rate Q may not change in the axial direction, as the fan is intubated. It follows that also the axial component c_x, for a given radius, must have the same value before and after the impeller, always assuming that the current surfaces are cylindrical. Therefore, if after the impeller c_x is constant with respect to the radius, because of equation (10) c_x will be constant with respect to r even before the impeller where, ultimately, lacking the tangential component c_u, the equation (7) will be satisfied without doubt. In other words with the Free Vortex the field of motion is with constant total energy also upstream of the impeller and, therefore, the impeller designed with this criterion provides the same energy to the air for all the values of the radius r.
The dark side of this advantage, is a lift coefficient C_L (par. 2.2) of the airfoil, that depends directly from c_u, which decreases rapidly with increasing radius r. In other words, toward the top, the blade "works" very little. Furthermore, there is a strong blade twist towards the hub.

2.1. Free Vortex method of axial fan design

To design the standard axial fans, the classic Free Vortex method is used. It starts from the definition of the typical number k, after imposing: the flow rate Q, the angular velocity ω of the impeller and the total specific energy (per unit mass) $\Delta p_0/\rho$ that the turbomachinery has to produce, according to:

$$k = \omega \frac{Q^{0,5}}{(\Delta p_0 / \rho)^{0,75}} \tag{11}$$

The dimensionless numbers Ψ, pressure number, and Φ flow number are defined as follows:

$$\Psi = \frac{p_0 / \rho}{u_e} \qquad \Phi = \frac{c_x}{u_e} \tag{12}$$

where: u_e is the tangential velocity at the external radius of the impeller ($u_e = \omega \cdot r_e$); c_x is the axial component of the absolute speed of the current; ρ is the air density that is held constant.
The next step is to use the data obtained experimentally that associate, for each typical number k, the corresponding values of these dimensionless numbers, Ψ e Φ, for which the axial fan presents the best fluid dynamic efficiency. Therefore, after obtaining these dimensionless numbers, Ψ e Φ, from the literature [8], the equations (12) furnish u_e, r_e, and c_x, where the last, by the law of free vortex, will be invariant along the radius of the impeller.
The turbomachinery theory [8], then, provides the following relationship between

the total specific energy produced $\Delta p_0/\rho$ and the tangential component of absolute velocity at the output of the impeller c_u, assuming that at the input of the impeller there is no tangential component of absolute velocity:

$$\frac{\Delta p_0}{\rho} = \eta_{id}\left(\frac{\Delta p_0}{\rho}\right)_t = \eta_{id} \cdot c_u \cdot u_e \tag{13}$$

where: $(\Delta p_0/\rho)_t$ is the total theoretical specific energy produced by the impeller (i.e. inclusive of internal energy losses at the impeller); η_{id} is the fluid dynamic efficiency that takes account of these internal losses.

By (13), assumed a value of fluid dynamic efficiency (η_{id}=0.75÷0.8), it can immediately derive the tangential component of the absolute velocity c_u at the top of the blade, i.e. at the radius r_e.

The use of (13) is greatly facilitated by the decision to use the law of the Free Vortex as mentioned in Section 2. In fact, the total specific energy produced by the impeller, $\frac{\Delta p_0}{\rho} = \eta_{id} \cdot c_u \cdot u_e = \eta_{id} \cdot c_u \cdot r_e \cdot \omega$, is constant with respect to the radius, because of the Free Vortex imposes: $r \cdot c_u = costant$. It is thus possible to use the (8), identifying the *constant* in the product $c_u \cdot r_e$, to derive the values of c_u with respect to the various radius values.

By (9), being c_x constant with the radius, the radius r_h at the hub of the fan will be immediately determined with the following law of the flow:

$$Q = \Omega \cdot \pi \cdot c_x \cdot \left(r_e^2 - r_h^2\right) \tag{14}$$

Where Ω is the obstruction coefficient: $\Omega = 1 - \frac{n \cdot s}{2\pi \cdot r}$; s is the blade thickness and n is the number of blades.

At this point, the properties of the velocity triangles at the input and output of the blade are used to determine the angle of inclination β_∞ of the average relative speed w_∞:

$$w_\infty = \frac{c_x}{sen\beta_\infty} \tag{15}$$

After choosing the number of blades n, and the length l of the chord of the airfoils, which, for the fan used in orchard sprayer, is imposed constant with respect to the radius r, it is possible to calculate the ratio between the pitch vane t and the chord l (inverse of blade solidity):

$$\frac{t}{l} = \frac{2\pi \cdot r}{n \cdot l} \tag{16}$$

and finally determine the lift coefficient:

$$C_L = \frac{2 \cdot c_u}{w_\infty} \frac{t}{l} \tag{17}$$

to verify if it is within the safe limits to avoid the stall, and then to take action by changing the number of blades and/or the length of the vane chord.
Finally, considering the particular expression of the law of Kutta-Jukowski, valid for aerofoils cascade that inspire the blade sections:

$$C_L = (0{,}094 \div 0{,}1) \cdot F_{es} \cdot i \tag{18}$$

and considering the experimental diagram of Weinig [9], which provides the interference factor F_{es} (cascade vs. isolated aerofoil) as a function of t/l ratio and of the angle β, formed by the direction of zero-lift with the normal to the axis of rotation of the fan and which is thus defined (with i that is the incidence angle, formed between the direction of zero-lift and the direction of the average relative speed w_∞):

$$\beta = \beta_\infty + i \tag{19}$$

through an iterative method, the values of i and β, can be finally determined. Then the values of i and β allow to quantify the constructive angle to the trailing edge of the aerofoil and, after having chosen the shape of the camber line (NACA, circular arc, etc.), they allow to calculate the complete geometry of the aerofoil. By performing the calculation from (15) up to (19) for different values of the radius it is possible to construct the entire blade.
The method, now outlined, is valid for the fans to the traditional air sprayer, for which the total specific energy under about 1000 Pa, values connectable to a number of blades (n=8÷10) and a length of the chord of the aerofoil (l=120÷150mm) that are typical of fan for the orchard sprayers.

3. New method for the design of optimized axial fan for the air carrier sprayer

3.1 Compound Vortex

Considering the ultimate goal of this work, which is to define a new fan design method for air carrier sprayers orientated to their downsizing, maintaining high performance, a new distribution law of the absolute tangential velocity c_u vs. radius r, was identified. It is based on the law of the Compound Vortex, here obtained by the method of trial and error, until to have the substantial constancy of the lift coefficient C_L vs. radius r:

$$c_u = \sqrt{A^2 + \frac{B^2}{r^2}} \tag{20}$$

Where A and B are constant to determine.
The choice of this type of Compound Vortex has also taken account of the simplicity of the solution of the equation (7) that, for the axial component of the absolute velocity c_x, provides:

$$c_x = \sqrt{\left(c_{xe}^2 - 2A^2 \ln \frac{r_e}{r}\right)} \tag{21}$$

where: c_{xe} is the axial velocity at the top of blade; r_e is the radius at the top of the blade (external radius of the impeller).
It is observed that by imposing the equation (7), and therefore the axial velocity c_x according to (21), a field of motion with constant total energy is produced in the downstream of the impeller which reduces the parasitic whirls and increases fluid dynamic efficiency η_{id}.

3.2 The mathematical model

The equations (20) and (21) contain four unknowns: the two constants A and B, the absolute axial velocity c_{xe} of air at the top of the blade and the external radius r_e of the impeller. These four unknowns are to be determined by imposing four conditions and then four equations.
The first condition to meet, concerns the air flow Q required to the fan. Given the variability of the axial air velocity c_x versus the radius r, the elementary flow rate must be defined: $dQ = \Omega \cdot c_x \cdot 2\pi \cdot r \cdot dr$, where Ω is the obstruction coefficient linked to the thickness of the blades as already done for Eq. (14). Therefore, to obtain the total flow rate of the fan, it must integrate after inserting the eq. (21): $Q = \int_{r_h}^{r_e} \left(1 - \frac{n \cdot s}{2\pi \cdot r}\right) \cdot \left(c_{xe}^2 - 2A^2 \ln\left(\frac{r_e}{r}\right)\right)^{0.5} 2\pi \cdot r \cdot dr$. However, the exact solution contains the Γ function, with the consequent difficulties of practical application. But, observing that the equation (21) provides a c_x velocity monotonically decreasing in the almost linear manner, it is possible to introduce an approximation which leads to the following equation between three unknowns (A, C_{xe} and r_e) and the flow rate Q required to the fan:

$$Q = \left(\pi - \frac{s}{r_e + r_h}\right) \cdot \left(c_{xe} \cdot r_e + \left(c_{xe}^2 - 2A^2 \ln\left(\frac{r_e}{r_h}\right)\right)^{0.5} \cdot r_h\right) \cdot (r_e - r_h) \tag{22}$$

This equation, with respect to the exact solution, produces errors lower than 1%. Furthermore it should be noted that in this process of calculation, the radius of the

hub r_h is known because it is imposed by the size of the mechanical members internal to the hub.
A second condition to meet, concerns the total specific energy $\Delta p_0/\rho$, that the fan must produce and which depends on the air pressure losses. These last, have to be calculated previously. The total specific energy produced $\Delta p_0/\rho$, now can not be calculated with eq. (13) proposed in Free Vortex method, because now the product $c_u \cdot u$ is not constant versus the radius r. Therefore, it is necessary to think of a weighted mean between the different values of the total specific energy with respect to the radius. Here it is proposed an integral mean, made by weighing the value of the total energy on the specific sections of the elementary flux tubes $2\pi \cdot r \cdot dr$.

$$\frac{\Delta p_0}{\rho} = \frac{2\pi}{\pi\left(r_e^2 - r_h^2\right)} \int_{r_h}^{r_e} c_u \cdot u \cdot r \cdot dr = \frac{2}{\left(r_e^2 - r_h^2\right)} \int_{r_h}^{r_e} \cdot \left(A^2 + \frac{B^2}{r^2}\right)^{0.5} \omega \cdot r^2 \cdot dr$$

The solution becomes:

$$\frac{\Delta p_0}{\rho} = \frac{2 \cdot \omega}{3\left(r_e^2 - r_h^2\right)} \left[\left(A^2 + \frac{B^2}{r_e^2}\right)^{0.5} \left(\frac{B^2}{A^2} + r_e^2\right) r_e - \left(A^2 + \frac{B^2}{r_h^2}\right)^{0.5} \left(\frac{B^2}{A^2} + r_h^2\right) r_h \right] \quad (23)$$

Then, the eq. (23) links three unknowns (A, B and r_e) and the total specific energy $\Delta p_0/\rho$ required to the fan. Furthermore, it should be noted that in this process of calculation, the angular velocity ω of the impeller is known, because it is imposed by the engine. But it can be varied, according to the limits of mechanical strength of the blades.
Finally, it is necessary to impose the condition that the lift coefficient C_L is constant along the radius r of the impeller. The lift coefficient is given by (17). Considering that the average relative speed w_∞ is linked to the c_x, c_u e u speed, on the basis of velocity triangles and inserting (20) and (21) in (17), we obtain:

$$C_L = \frac{2 \cdot \sqrt{\left(A^2 + \frac{B^2}{r^2}\right)}}{\sqrt{\left(c_{xe}^2 - 2A^2 \ln\left(\frac{r_e}{r}\right)\right) + \left(\omega \cdot r - \frac{1}{2}\left(A^2 + \frac{B^2}{r^2}\right)^{0.5}\right)^2}} \frac{2\pi \cdot r}{n \cdot l} \quad (24)$$

The analysis of the function (24) $C_L = f(r)$, allowed to understand that the condition $C_L = costant$, can be obtained in a simplified way by imposing: $C_{Le} \cong C_{Lh}$ and $C_{Le} \cong C_{Lm}$, where C_{Le}, C_{Lh}, C_{Lm} is the lift coefficient, respectively, at the top of the blade (external radius of the impeller), at the hub of the impeller and at the medium of the blade. Using (24), we obtain:

$$\frac{A^2 r_e^2 + B^2}{c_{xe}^2 + \left(\omega \cdot r_e - \frac{1}{2}\left(A^2 + \frac{B^2}{r_e^2}\right)^{0.5}\right)^2} - \frac{A^2 r_h^2 + B^2}{c_{xe}^2 - 2A^2 \ln\left(\frac{r_e}{r_h}\right) + \left(\omega \cdot r_h - \frac{1}{2}\left(A^2 + \frac{B^2}{r_h^2}\right)^{0.5}\right)^2} \leq \varepsilon \quad (25)$$

$$\frac{A^2 r_e^2 + B^2}{c_{xe}^2 + \left(\omega \cdot r_e - \frac{1}{2}\left(A^2 + \frac{B^2}{r_e^2}\right)^{0.5}\right)^2} - \frac{A^2 r_m^2 + B^2}{c_{xe}^2 - 2A^2 \ln\left(\frac{r_e}{r_m}\right) + \left(\omega \cdot r_m - \frac{1}{2}\left(A^2 + \frac{B^2}{r_m^2}\right)^{0.5}\right)^2} \leq \varepsilon \quad (26)$$

Where ε is vanishing. For the calculations shown in the next Section 4, it was taken: $\varepsilon = 0.01$.
Ultimately, the solution [10] of the four equations system (22), (23), (25), and (26), allows to obtain the values of the four unknowns: the two constants A and B, the absolute axial speed c_{xe} of the air at the top of the blade and the external radius r_e of the fan.
The calculation procedure, which leads to the design of airfoils of the blade, is completed with the use of the equations (18) and (19), following the guidelines in the final part of the previous Section 2.

4. Results

The classic method based on the Free Vortex, described in Section 2.1, has been followed, obtaining the design of a traditional fan for air carrier sprayers with r_e = 0.5 m (D_e=1000 mm). First of all the lift coefficient to the hub C_{Lh} equal to the maximum value allowed of 1.2, the angular velocity ω=210 s^{-1}, the number of blades n=10, the length of the vane chord l=0.12 m and the radius of the hub r_h=0.125 m, were imposed. Then, the equations from (11) to (19) were applied, obtaining a flow rate Q=58,400 m^3/h and a total specific energy $\Delta p_0/\rho$ =525 m^2/s^2. The speed values of c_u, c_x e w_∞ vs. the radius r are shown in Figure 2 (left), while the lift coefficient C_L is shown in Figure 2 (right).

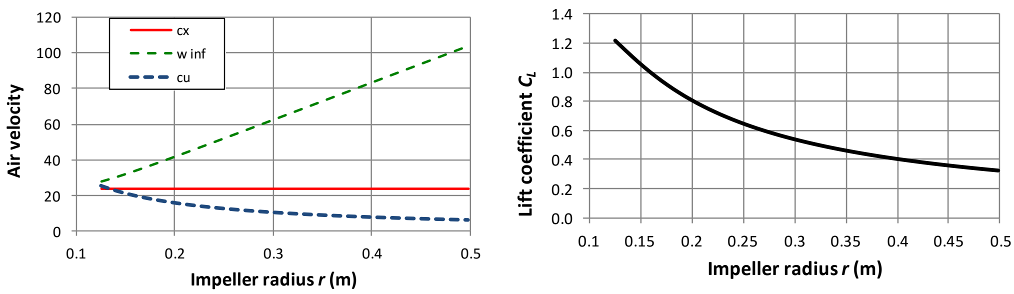

Fig. 2 – Free Vortex method: tangential c_u and axial c_x component of absolute air velocities (left); mean relative (to airfoil) air velocity w_∞ (left). Lift coefficient C_L vs. impeller radius (right).

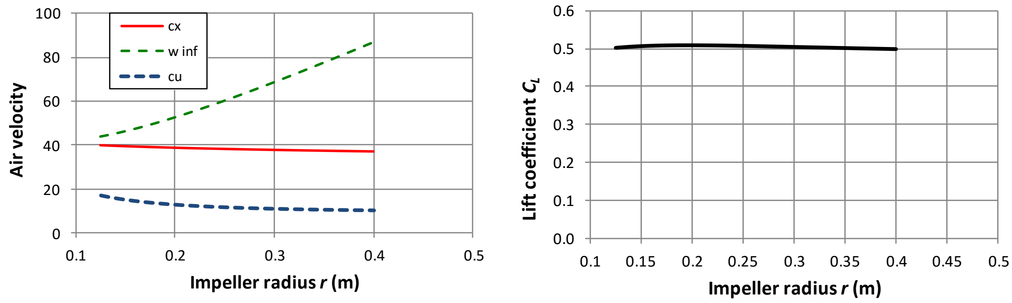

Fig. 3 – Compound Vortex method: tangential c_u and axial c_x component of absolute air velocities (left); mean relative (to airfoil) air velocity w_∞ (left). Lift coefficient C_L vs. impeller radius (right).

By imposing the same flow rates Q = 58.400 m^3/h and the same total specific energy $\Delta p_0/\rho$ =525 m^2/s^2, the new method described in Section 3, and based upon the special Compound Vortex, was then applied. Thus, the speed values c_u, c_x e w_∞ vs. the radius *r* obtained, are shown in Figure 3 (left), while the lift coefficient C_L is shown in figure 3 (right).
But the most important is the downsizing obtained. It is represented by an external radius r_e=0.4 m (D_e=800 mm vs. 1000 mm), that is by a reduction of diameter of a factor 0.8.
It is interesting to observe that the lift coefficient C_L meets the condition set to be constant, but it has values about half the stall limit. So, an increase of C_L is possible, which can used to produce an increase in total specific energy required to the fan, for example if an increase of the air outlet speed from the edge of the air carrier sprayer, is required. This is impossible for the fan designed with the Free Vortex method, because the stall limit to the hub had already been reached.
Finally it is interesting to see, from a comparison of Figures 2 (left) and 3 (left), that the w_∞ speed (as average on all length of blade) is respectively 64 and 60 m/s. Since it is the speed with which the air flows between the blades, it is also an indicator of energy losses and thus of the fluid dynamic efficiency. So, finally, the efficiency η_{id} does not decrease with the new design method.

5. Conclusions

Given that today the new vineyard and orchard systems are made with a high intensity of plants per hectare and therefore with a much smaller distance between rows respect to the past, the manufacturers of tractors and sprayers are forced to reduce the width of the machines.
Especially, it is also necessary to study a method for the design of axial fans installed in atomizers, so that they are of small diameter, while maintaining the performance required by the agrochemical treatments. Starting from a fluid dynamic study of the fans, the goal of the work was directed to the search for a new design criterion.

This criterion was found in a law of variation of the tangential component of absolute velocity exiting the fan that follows a Compound Vortex. To keep the field of motion with constant total specific energy also along the radial direction, the differential equation of motion was then resolved to find the law of variation of the axial component of the absolute velocity. The complexity introduced, has therefore required the definition of a mathematical relationship between the flow rate and the aforementioned absolute velocities of the air and also between the specific total energy and the same velocities. Finally, a condition that will lead to a reduction of the external diameter of the fan impeller, was imposed. This condition was that the lift coefficient remain constant along the radius. Solving the previous system of equations, all the values design parameters of the fan were derived. Ultimately, with this new method, there is a reduction of the outer diameter of the fan by a factor of 0.8, but also a reduction of the lift coefficient, precisely because imposed constant vs. the radius. So, there is a margin in order to further increase the fan performance in terms of total specific energy. Finally, the calculation of the average relative speed, allowed to say that there is not a deterioration of the fluid dynamic efficiency.

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