The Swirling Jet Generation Method and Its Effect on the Velocity Distribution

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Abstract: The wing tip vortex has a great similarity with the swirling jets. Since these are generated of a simpler and more economic form in a laboratory, it is relevant to determine which the best method is for the generation of the swirling jet. In this paper, the velocity distribution obtained experimentally with the method of generation here proposed, which consists of the employment of an axial fan without stators, is compared with the velocity distribution of swirling jets generated with three different methods. It is observed that the velocity distribution obtained with the proposed method is similar with one of the methods found in the references, which uses fixed blades guides at the entry of the pipe. The proposed method is suitable for the generation of the swirling jet and it is considered that it is simpler and more economic to use blades fixed guides.

Key words: Swirling jet, velocity distribution, swirl intensity, wingtip vortex, tangential velocity.

1. Introduction

Swirling jet is characterized by a tangential or azimuthal velocity component, superimposed on axial velocity and occurs when a swirling flow is ejected from a circular hole in the external fluid environment, which can be at rest or co-flowing. Swirling jets are important in many technical and industrial applications. For example, they are used in combustion systems to improve cooling by forced convection, to promote and increase the turbulent mixing of the jet of atomized fuel with the adjacent air and also to stabilize the combustion zone due to the presence of the central recirculation region of the self-induced vortex [1].

At Escuela Superior de Ingeniería Mecánica y Eléctrica (ESIME) Ticomán through research in swirling flows and jets, it has been established that the swirling jet has similarities with the trailing edge vortices of a wing mainly when they have reached the status of a couple of wingtip vortices. On this condition, the tangential velocity of the wing tip vortex has a very similar behavior to the tangential velocity generated by the swirling jets. For this reason and because of the difficulty and high cost of performing measurements on vortices that are detached from the wings, it has been established that to realize measurements in a swirling jet can generate useful information for more detailed knowledge of the generation, development and evolution of the wingtip vortices as well as for the control and decrease of intensity of the same ones. The information would be useful to develop technology in order to decrease the intensity of the wingtip vortices which would lead to more efficient operation of airports since it could reduce the separation between aircraft during takeoff and landing and could decrease serious effect on small aircraft when these encounter the wake turbulence from large aircrafts [2].

From the literature review, we found that the swirling flow can be generated experimentally in various ways, which can be grouped into three types [3]:

(1) Rotating Method as illustrated in Figs. 1a and 1b, in which the tube through which fluid flows
rotates about its axis. In some cases, at the entrance of the tube a flow divider is placed, thereby increasing the tangential velocity and in others a honeycomb is placed inside the rotating tube (Fig. 1b) in order to generate a swirling flow closer to a laminar flow. Also, both methods of generating the swirling flow have used a converging nozzle before the flow leaves the pipe, which affect in different way the axial and tangential velocity distribution of the swirling jet, although in both cases it shows an increase in both speeds [3].

(2) Injection Methods of secondary flow as shown in Figs. 1c and 1d. In this method, a tangential secondary flow is injected to an axial primary flow. Tangential Flow Injection may be external (Fig. 1c) [4] or internally to the main tube (Fig. 1d). The swirl intensity is controlled by the amount of mass flow injected tangentially.

(3) Passive Methods as those shown in Figs. 1e and 1f. These methods have different variants, since the colocation of fixed blades guides at the inlet of the flow (Fig. 1e) [5] until the insertion of helical strips in the inner tube, which are those that induce the swirl (Fig. 1f).

The bibliographical research shows that the experimental methods most used to generate the swirling jet are the type 1 mainly with honeycomb inside with or without nozzle (Fig. 1b) and type 3 using fixed blades guides at the tube entrance (Fig. 1e).

In our case, it was found that the flow produced by an axial fan without a flow straightener (stators), generates the swirling flow easily, so it is the device that is selected here for generating the swirling jet. This method is similar to that shown in Fig. 1e but it is simpler because the fan blades, when they rotate in addition to generating the axial flow also generate a tangential velocity, while the method of Fig. 1e requires

Fig. 1  Methods of swirling flow and jet generation.
Source: adapted from Refs. [3-6].
an additional device for generating the axial flow. The advantage of the method of fixed blades guides is that it allows better control of the intensity of the swirl but is required to verify that the flow is purely axial before it reaches the inlet fixed blades guides.

1.1 Reynolds Number and the Intensity of the Swirling Flow

In general, the Reynolds number of an axis-symmetrical jet is based on nozzle radius, \( R \), which generates the jet and the axial velocity on the jet axis, \( W \), or the bulk velocity, \( W_0 \).

\[
R_e = \frac{2RW_0}{\nu}
\]  

In Eq. (1), \( \nu \) is the kinematic viscosity.

The definition of the swirl intensity (S) varies between different references. One common way is to express the swirl intensity as the ratio of the tangential to axial momentums. However, this definition implies that the distribution of axial and tangential velocity must be measured accurately through the jet orifice so that it can perform the calculation of the corresponding flow momentums [5, 6]. In some cases, this is not possible or is impractical, so other definitions have been suggested. Ref. [3] indicates that Chervinsky and Chigier proposed that the swirl intensity could be determined as the ratio between the maximum tangential velocity, \( V_{\text{max}} \), and the maximum axial velocity, \( W_{\text{max}} \) at the hole whereas Billant et al. propose that the swirl intensity is the ratio of the tangential velocity measured at half the radius of the nozzle which generates the jet to the axial velocity in the axis of the jet to an approximate distance of a diameter, downstream of the jet outlet. For the case where the swirl is produced by rotating the tube through which the flow is driving, Facciolo [3] states the swirl intensity as the ratio of the tangential velocity at the tube wall (tangential maximum speed) and the bulk velocity. For our case is more appropriate the definition of Chervinsky and Chigier, that is:

\[
S = \frac{V_{\text{max}}}{W_{\text{max}}}
\]  

1.2 Velocity Distribution Obtained with the Different Methods of Generating Swirling Jet

In the references consulted, experimental information about the following methods of generating swirling jet, was found.

1.2.1 Rotation of a Cylinder with a Honeycomb Inside

The axial and tangential velocity distribution is shown in Figs. 2 and 3. The axial velocity is normalized with respect to the bulk velocity (\( W_0 \)), while the tangential speed is normalized with the tangential velocity in the wall (\( V_w \)). The measurements were made with hot-wire anemometry and laser-Doppler anemometry for two intensities of swirl and three axial distances downstream of the jet exit plane [3], in Figs. 2 and 3 only the measurements for \( x/D=0 \) and for \( S=0.5 \) are shown.

1.2.2 Rotation of a Cylinder with a Honey Comb Inside and a Nozzle at the Outlet

The axial and tangential velocity distribution normalized with the measured speed at the center of the exit plane without rotation (\( W_1 \)) is shown in Fig. 4. Measurements were done with hot-wire anemometry in the jet exit plane using a nozzle with an area ratio of 4 [7].

1.2.3 Fixed Blades Guides at the Entrance of the Tube

Experimental measurements of the axial velocity and the tangential velocity normalized are shown in Fig. 5. In the reference of which was obtained this figure did not indicate the instrumentation used, neither the speed that was used as reference to normalize the speeds nor the swirl intensity generated, only it described that measurements were made in a plane located 25 mm downstream of the plane jet exit.

Comparing the above experimental data, it is noted that the cases 1 and 2 are very similar in terms of the shape and behavior of both the axial and tangential
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velocity distribution (Figs. 2-4), however with respect to case 3, the velocity distribution differs markedly mainly with respect to the axial velocity as Fig. 5 shows a region of negative axial velocity at the center of the jet, which is not observed in the cases 1 and 2 (Figs. 2 and 4). With respect to the tangential velocity, the velocity distribution is quite similar in all three cases, however in case 3, the data show a greater dispersion in the central region and do not display a symmetry between the regions of positive and negative speed, as it happens in cases 1 and 2.

Fig. 2  Dimensionless axial velocity distribution.
Source: adapted from Ref. [3].

Fig. 3  Dimensionless tangential velocity distribution.
Source: adapted from Ref. [3].
2. Equipment and Methods

The experimental equipment used for this research consists of the following devices.

2.1 Device for Generating the Swirling Jet

The equipment used to generate the swirling flow is shown in Fig. 6 and is located at the Hydro-pneumatic Laboratory of the ESIME Ticoman. It consists of an axial fan of six blades of 0.3 m in diameter driven by a single-phase motor of 0.125 HP and a rheostat that regulates the engine rpm in the range of 400 to 4,800 rpm and is coupled with a metallic nozzle to a tube of...
circular cross section having an internal diameter of 0.184 m and 1.300 m long. The duct is formed of three sections of pipe, the two end portions are fixed and measure 0.300 m and 0.250 m and the central section measures 0.750 m and can rotate, although this last facility was not used. In order to generate the swirling flow, the fan was stripped off the flow straighteners. The minimum speed of rotation of the fan (400 rpm) was used since at this speed, it achieved a large intensity of swirl, estimated at 0.645 using Eq. (2) and a bulk velocity of 0.42 m/s suitable for the speed of the linear actuator that is used to implement the measurement technique called hot-wire flying. With this bulk velocity a Reynolds number of 4,415 was obtained.

2.2 Hot Wire Anemometry System and Device to Move the Sensor

The hot-wire anemometry at constant temperature (CTA) system used is called streamline and it is manufactured by Dantec, which uses the software called Stream Ware for processing the signals obtained [9]. The one-dimensional sensor used is the 55P11 sensor. A frequency of 1 kHz was used for data acquisition, whereby a velocity value is obtained every millisecond.

The selected device to move the hot wire sensor is a device manufactured by Yaskawa called Sigma Trac Linear Servo System, consisting of a linear servomotor which is composed of a travelling coil formed of a laminated iron core and fixed magnetic guide. Servomotor control is performed by a servo amplifier model Sigma II and controller Legend-MC both made by Yaskawa. This system works with 125 V alternating current, has a power of 125 W, maximum acceleration of 50 m/s² and the maximum speed of 3 m/s in the race against the swirling flow. The rate of return is slower and is not used for measurement, that is, the motor operation is not continuous. Fig. 6 shows the complete installation.

The speed of the linear servo motor is the speed with which the hot-wire sensor is moving, so it must have a constant speed during the trip as long as possible. Since the maximum speed of 3 m/s (VML3) is achieved only for a short time it was decided to use the speed of 2 m/s (VML2) as this is maintained for 0.18 s, for a total race time of 0.379 s, as shown in Fig. 7, where also the speed of 1 m/s (VML1) is shown.

2.3 Aeroprobe Measurement Equipment ESP/Probe Acquisition System (AP3000 System)

The measuring equipment is shown in Fig. 8a and consists of the following elements [10]:

(1) Sensor of 7 holes made by Aeroprobe (Fig. 8b). It is built of machined brass cone-shaped with a semi-angle
Fig. 7 Velocity of the hot-wire sensor.

Fig. 8 Aeroprobe system, sensor of seven holes.
of 30°, has 7 welded tubes that connect the holes at the tip brass pressure sensors to the scanner. It also has an arrow that serves to hold the sensor.

(2) Miniature electronic pressure scanner model ESP-16HD made by Pressure Systems (Fig. 8c), which is a unit that measures the pressure difference in each hole of the sensor and consists of 16 pressure piezo-resistive sensors. The scanner outputs are taken to an amplifier where it changes the analogue signal to digital (Fig. 8a).

(3) Software Aeroacquire, which calculates the speed and direction of flow from the pressures taken at each sensor hole.

3. Results and Discussion

3.1 With Flying Hot Wire Technique

With this technique it was not possible to obtain the velocity distribution as a set of sensors moving simultaneously are required, however it was possible to demonstrate that at the swirling jet axis the reverse flow occurs, as indicated by the shaded area in Fig. 9. This figure was prepared with the speeds that directly calculated the Stream Ware software each millisecond, both for the speed of the sensor (without air flow) as to the relative speed of the flow sensor (the sensor speed plus the flow of air). The axial velocity of the swirling flow is obtained by subtracting the sensor speed to the relative speed. As noted, the velocity along the jet axis is variable and in a few moments it becomes positive. The mark \( x/D = 6 \) delimits the flow within the tube and outside the tube, that is, the swirling jet. From this point, which corresponds to 0.28 s, the flow is inside the tube.

3.2 With the Aeroprobe System of 7 Holes

Experiments were carried out by measuring the axial and tangential velocity of the swirling jet at different radial positions from zero to \( \pm 12 \) cm with one-centimeter increments. The magnitudes of the velocities are calculated directly by the software Aeroacquire. These

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**Fig. 9** Reverse flow in the axis of the swirling jet, obtained with the technique of the flying hot wire.
measurements were performed only in the axial position zero (immediately after the flow outlet). The measurements were repeated 5 times in order to find an average speed for each radial position. The average axial and tangential velocity obtained was plotted in Excel. With the plotted points we found polynomial trend lines of degree 6, which is shown in Figs. 10 and 11. In Fig. 10 the axial velocity distribution is shown and in Fig. 11 the tangential velocity distribution, both for station $x/D=0$.

4. Analysis of Results

Acquired data show that axial and tangential velocity distributions have a greater resemblance to the experimental data obtained from Ref. [8] (case 3 of swirling jet generation, Fig. 5), which proves that
the method of swirling jet generation here used is similar to the method that uses the fixed blade guides at the tube entrance. The main similarities and differences are as follows:

(1) Using the Aeroprobe system was not possible to find negative axial velocities in the center of the jet, as reported in Ref. [8], although the decrease in speed in that region is detected, appearing at the center of the jet the lower axial velocity. However, using the hot wire flying technique is possible to detect negative axial velocity regions (reverse flow) mainly in the axis of the jet. With additional measurements made at higher radial positions, it was found that for locations \( r/D = 0.15 \) the reverse flow is no longer presented.

(2) The axial velocity distribution obtained shows the same asymmetry that is reported in Ref. [8]. In both cases, there are two maximum axial velocities but with different values and in both cases the lower maximum axial speed occurs in the middle of the swirling jet radius where the tangential velocity is negative.

(3) Comparing tangential velocity distribution with the reported in Ref. [8], a similarity is noted in the dispersion of data that exists in the center of the swirling jet although the data reported here show higher symmetry. It is also not consistent with Ref. [8] in the fact that the maximum tangential positive and negative velocities reported differ by approximately 20%, being greater the tangential positive velocity, while the maximum tangential velocities reported here are virtually identical.

(4) With respect to the location of the maximum axial and tangential velocities, we observe that in Ref. [8] these values are presented in radial positions that match the tube wall for where the swirling jet exits \( (r/D = \pm 0.5) \), while our measurements show that this happens at \( r/D = \pm 0.3 \) for the maximum tangential velocities and \( r/D = \pm 0.37 \) for the maximum axial velocities.

5. Conclusion

It has been shown that the method of generating swirling flow and jet has significant effects on the velocity distribution mainly in the axial velocity, so care must be taken when using these data. It has also been shown that the methods of generating the swirling jet with fixed blade guides, and by an axial fan without stators produce a fairly similar jet stressing here that the method used in this study is simpler and more economical.

Regarding Aeroprobe system, it was found that this system has low repeatability, which is attributed to the high turbulence of the swirling jet and therefore not suitable for precision measurements of the characteristics of the flow, however in the different series of measurements made, the trend lines describing the axial and tangential velocity distribution were found to be quite similar. By the above, it is considered that the analysis to determine the effect of the method of generating the swirling jet velocity distribution is suitable.

Finally, it is important to highlight the relevance of the instrumentation used to perform precise measurements of the velocities, since as noted, the reverse flow that can generate a swirling jet can only be detected with sophisticated anemometers and techniques such as flying hot wire and laser-Doppler anemometry.

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