S-TYPE PITOT TUBE CALIBRATION BY MEANS OF LDA TECHNIQUE

Giuseppe Dinardo [1], *Paolo Pietroni* [2], *Gaetano Vacca* [3]

[1] Politecnico di Bari, Bari, Italy, dinardo@imedado.poliba.it
[2] Gruppo Loccioni, Angeli di Rosora (AN), Italy, p.pietroni@loccioni.com
[3] Politecnico di Bari, Bari, Italy, g.vacca@poliba.it

Abstract: The paper describes an innovative, more accurate and reliable method for calibrating S-type Pitot tubes (SPT) by means of Laser Doppler Anemometry technique (LDA). Due to its coarse structure (since it is used in chemically aggressive environments), it requires periodic calibrations, which are carried out by means of a more accurate standard L-type Pitot tube (LPT). The use of LDA as standard allows overcoming the drawbacks inherent in the usual calibration technique.

Key words: Pitot tube, S-type Pitot tube, Laser Doppler anemometry, calibration, stack gases.

1. INTRODUCTION

In the field of combustion processes, where pollutant or chemically aggressive substances are involved, an accurate evaluation of the volumetric flow rate of stack gases is required, in order to fulfill the environmental regulations [1]. Currently this is achieved by means of an S-type Pitot tube [2], which is characterized by a coarse geometry, allowing its use in aggressive environments.
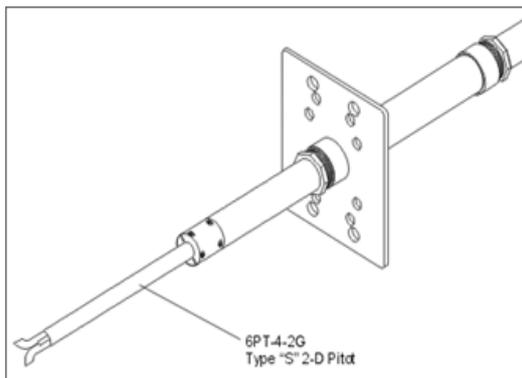

Fig. 1. S-type Pitot tube

Its geometry requires it to be undergone to periodic calibration which is usually carried on against a more accurate L-type Pitot tube (LPT), with a known calibration coefficient C_s.

The SPT (as the LPT) is used to measure point velocity of fluid flows and its principle of operation is based on the Bernoulli equation, which provides local velocity (where the instrument is located) by measuring the local dynamic pressure sensed at both legs of the instrument and measured by an appropriate differential manometer. The dynamic pressure is the difference between the stagnation pressure (sensed by the frontal or total SPT leg) and the static one, sensed by the rear leg, to give:

$$v = C_s \sqrt{\frac{2\Delta p}{\rho}} \qquad (1)$$

The term v is the calculated local velocity; Δp the measured dynamic pressure sensed by the Pitot tube and ρ refers to the fluid density. Since the flow is not properly ideal a correction factor C_S (namely calibration coefficient) must be taken into account.

Calibrating an SPT means determining its calibration coefficient C_S. Currently this is carried out by means of an LPT [2-5] having a known calibration coefficient C_L. Employing the generalized Bernoulli equation (1), the term C_S can be determined as follows:

$$C_S = C_L \sqrt{\frac{\Delta p_L}{\Delta p_s}} \qquad (2)$$

where Δp_L and Δp_s respectively indicates the dynamic pressures sensed by LPT and SPT.

2. PURPOSE AND METHODOLOGY

The SPT calibration procedure, briefly described in the previous section, implies the preliminary installation of the LPT in the cross test section of the tunnel, where a gas flow (of known properties) is established. Once the term Δp_L is measured, the LPT is removed and then replaced by the SPT, to be installed in the same cross section. These operations imply several drawbacks. The replacement itself compromises the entire procedure reproducibility. Furthermore an additional source of uncertainty arises from the difference between the geometries of the two Pitot tubes, so implying different locations in the flow where the pressures are sensed, thus making them measuring velocities of different points. Furthermore, the SPT calibration is performed at a single determined fluid flow velocity in the test tunnel. A more accurate and precise evaluation of the C_s coefficient would require measurements made at several fluid flow velocities within the velocity range of interest (usually 10 m/s up to 25 m/s).

2.1. Brief description of LDA technique

In this paper an alternative procedure of calibration based on LDA is described.

The Laser Doppler Anemometry technique provides many advantages. In first instance, due to laser light properties such as high spatial and temporal resolutions, it is really able to perform point measurements, since the measurement volume (generated by the intersection of the incident laser beams) is of the order of several micrometers. In addition, the LDA technique is not affected by loading effects, thus requiring only an optical access to the measurement environment where to make the laser beams intersecting.

These advantages allow the direct measurement of fluid flow velocities where the measurement volume (generated by laser beams intersection) takes place.

2.2. SPT calibration by means of LDA: description of the methodology

The employment of a laser Doppler anemometer as reference instrument to calibrate an SPT against removes the main and most prominent source of uncertainty found in the conventional calibration method: the need for an LPT which implies the replacement procedure.

In addition, by providing a limited part of the wind tunnel wall with an appropriate optical access, it is possible to focus the measurement volume in front of the SPT leg sensing the stagnation pressure.

The analytical model used for the determination of C_S coefficient, is given by the following equation 3:

$$v_{LDA} = C_s \sqrt{\frac{2\Delta p_s}{\rho}} \qquad (3)$$

The term v_{LDA} refers to the point velocity measured by the laser anemometer, ρ indicates the gas density (to be measured), Δp_s the dynamic pressure sensed by the SPT under calibration and C_s the SPT calibration coefficient.

The LDA used for the calibration is the *Flow Lite System 2D* manufactured by *Dantec Dynamics®* which allows 2D measurements.

After the SPT installation in the cross test section, the measurement volume generated by the anemometer has been converged in the front of SPT total port (sensing the stagnation pressure). Through a differential manometer the dynamic pressure Δp_s sensed by the Pitot tube has been measured.

In order to achieve a better evaluation of C_S with its own uncertainty, the measurements have been taken at several fluid flow velocities within the usual range of operation of the S-type Pitot tube (10 m/s up to 25 m/s). The variation of flow velocity through the wind tunnel has been achieved by setting the angular velocity of a fan installed at the rear of the wind tunnel.

For a better C_s evaluation, other important aspects have to be considered. Since the SPT has a squat shape, its openings (which range from several millimeters up to 1 cm) are too large. Thus the dynamic pressure sensed by the Pitot tube is an average over the several streamlines at the total port of the SPT. On the other hand, the LDA measures the velocity of the seeding particles (which are carried by the fluid flow) crossing the measurement volume. Then the measurements made by the laser anemometer are indicative of point velocities.

In order to take into account this, the LDA measurement volume has been moved to get the velocity of 5 points in the same cross section in front of the SPT total port (illustrated by fig. 2), sufficiently far from not to sense any disturb from it. At each point time several repetitions have been taken, depending on LDA Data Rate (which depends mainly on flow seeding condition). These time repetitions from each of the five measurement points have been treated with ANOVA (ANalysis Of VAriance), in order to assess their homogeneousness. The ANOVA has been used to statistically test whether or not the means of the time repetition samples (and their own standard deviations) are unbiased.
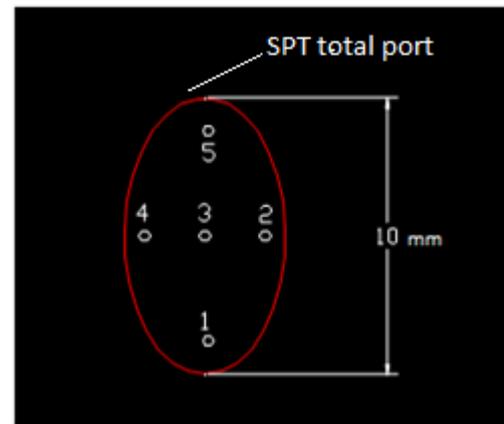

Fig. 2. Measurement points of lda

Once the success of the ANOVA test is achieved, in order to take into account the time repetitions at each point and the spatial replications achieved at the five measurement points, the measurements made with the LDA have been treated with the pooled statistics [6]. This is to get the mean value and an estimator of the standard deviation of the fluid velocity for each fan speed.

A further important factor to be mentioned is the blockage effect caused by the insertion of the Pitot tube under test in the wind tunnel. Since the flow involved in the test (made by air at standard conditions) is incompressible, with Mach < 0.3, and since the volumetric flow rate has been constant at each fan speed, the blockage effect implies the fluid flow velocity increase at the cross section where the Pitot tube is inserted. This effect leads to an increase of $\sqrt{\Delta p_s}$ (eq 1), implying an incorrect evaluation of C_s. From equation (3), the rise of $\sqrt{\Delta p_s}$ implies a decrease of C_s, since v_{LDA} is measured through the laser anemometer and it is relatively uninfluenced by the blockage effect (the measurement volume generated by laser beams intersection has been located sufficiently far from the cross section where the SPT has been installed).

This drawback can be overcome by multiplying the right side of (3) by a correction coefficient, leading to the following expression:

$$v_{LDA} = \bar{C}_s \frac{A - A_S}{A} \sqrt{\frac{2\Delta p_s}{\rho}} \qquad (4)$$

In the previous, the term $\frac{A-A_S}{A}$ is the blockage factor (where A is the cross section and A_s the reduced one). The so defined calibration coefficient $\bar{C}_s$ does no longer take into account the blockage effect.

The proposed correction is essential if the blockage factor is significantly smaller than unity. In the measurements performed by the authors of the paper, the blockage factor is 95% or 0.95 and it has been taken into account.

2.3. Results

The following table (Table 1) reports data concerning the measurement of v_{LDA} with the laser anemometer and the measurements of dynamic pressures sensed by the Pitot tube.

Table 1. Experimental data.

V_{LDA} m/s	u_{vLDA}	$\sqrt{\Delta p_s}$ $\sqrt{Pa}$	$U_{\sqrt{\Delta p_s}}$
9.36	0.01	9.36	0.49
11.10	0.01	11.04	0.62
13.43	0.01	14.01	0.52
16.38	0.01	16.81	0.57
19.34	0.01	20.01	0.54
22.30	0.01	22.26	0.62
25.26	0.02	26.33	0.56

Each row of the table reports the results in terms of velocity and pressure drop from the experimental data taken at each angular velocity of the fan (supplied by an asynchronous AC motor which frequency can be tuned by an inverter). The second and forth columns report the standard uncertainties of v_{LDA} and $\sqrt{\Delta p_S}$ respectively.

2.4. Calibration curve and further discussions about the results

The data have been plotted on Table 1 and then the calibration coefficient $\bar{C}_s$ (the corrected one because of the blockage effect considered here) has been evaluated from the slope of linear regression (from eq. 4, $\bar{C}_s$ is proportional to the curve slope and it has been determined once the air density ρ has been measured).
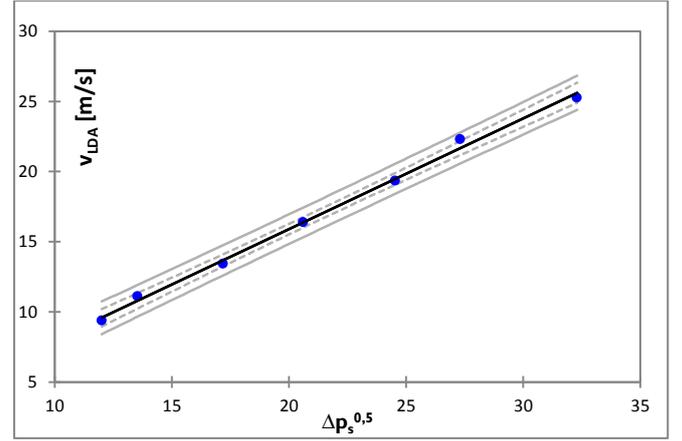

Fig. 3. Least squares regression of the model (4)

Fig. 3 reports the linear least squares regression of the model expressed by eq. (4). The correlation coefficient R^2, assessing the goodness of the fit, is 0.996 and $\bar{C}_s$ is given by:

$$\bar{C}_s = 0.80 \pm 0.05 \qquad (95\%)$$

3. CONCLUSION

The main purpose of the article is to propose an innovative and more accurate method for the calibration of an S-type Pitot tube by means of a laser anemometer.

The SPT, because of its quite coarse structure, is mainly employed in exhaust gases or chemically aggressive environments, where the risk of clogging caused by particles is high. Such a characteristic implies a periodic characterization of the Pitot tube in order to get accurate and precise evaluations of volumetric flow rate of the pollutant content of exhaust gases.

There are papers and publications [2-5] mainly by the Environmental Protection Agency, prescribing the SPT calibration method and other prescriptions in order to properly use it. These calibration procedures require the use of a more accurate L-type Pitot tube as standard.

Several drawbacks arise from conventional methodology, including the consequent replacement process, necessary in order to carry out the calibration, posing a serious threat to the reproducibility of the procedure. Furthermore the calibration with an LPT is performed at a single fluid flow velocity (the mean value within the usual range of operation of SPT). Instead, an accurate calibration procedure would require measurements performed at several flow velocities within an established range.

These disadvantages can be overcome by performing the measurements at several flow velocities by means of a laser anemometer.

The LDA advantages have already been described in this paper. The most relevant one consists of the chance of performing velocities measurements with the SPT installed and sensing the dynamic pressure at each fan speed. This allows faster measurements and the chance of easily performing the entire calibration cycle over the selected velocity range. Assessed the reproducibility of this

methodology, it is possible to esteem the better accuracy and precision led by the proposed method.

In order to get more accurate evaluations, other important elements have been considered, such as blockage effect and the need of performing spatial replication, taking into account the relatively large inlet port of the S-type Pitot tube.

The blockage effect has to be taken into account whenever the Pitot tube input port section and the cross test section ratio is not negligible. If the flow is incompressible (which is the case) and the flow rate is kept constant at each fan speed, the SPT insertion in the wind tunnel leads to the increase of fluid flow velocity. By equation 1 an increase of the dynamic pressure occurs. If the effective velocity is measured with the laser Doppler anemometer in a point not disturbed by the SPT insertion, the blockage effect causes a decrease of the calibration factor. Thus a correction coefficient (eq. 4) is required.

The need of performing spatial replications distributed across the SPT inlet port (as Figure 2 illustrates) with the laser anemometer is implied by the coarse geometry of the SPT itself. It senses several streamlines which are captured by the relatively large inlet opening. Since the LDA allows point fluid flow velocity measurements, the area across the SPT inlet opening has to be mapped and a mean value for the velocity measured with the LDA has to be calculated. In this paper, these calculations have been performed using the pooled statistics which allows to treat data relating to the samples of time repetitions made at each of the five points of measurements and of the spatial replications obtained by moving the LDA measurement volume.

By analyzing the characteristics of such a calibration method, other important aspects have to be mentioned.

The differential pressure sensed by the SPT is not the effective dynamic pressure (as the difference between the stagnation pressure at the SPT inlet port and the static one). In fact, the coarse structure of the SPT implies a change of the pressure distribution around the Pitot tube. The SPT legs provoke pressure waves reflections which affect the stagnation pressure sensed by the inlet port. Moreover the important weak effect at the back port of the SPT affect the stagnation pressure measured by the tube. Nevertheless these effects, which could be considered as insertion effects, are taken into account by the calibration procedure itself.

One other aspect to consider is the fluid compressibility. The used model, based on Bernoulli equation, has consistency whenever the Mach number is lower than 0.3 (which is the case). In the case of stack flows with Mach numbers larger than 0.3, the compressibility effects couldn't be neglected and the Bernoulli model (expressed by eq. 1) should be adequately corrected.

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