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A 2-PORT, SPACE-SAVING, MAINTENANCE-FRIENDLY PNEUMATIC PROBE FOR VELOCITY MEASUREMENTS

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Abstract

This paper presents the concept, design and experimental results of tests, in laboratory conditions, of a 2-port, space-saving pneumatic probe. The main features of the probe are a result of restrictions imposed by the functioning environment: a limited space for probe installation, the possibility of processing only two output signals and requirements for simplicity and reliability of the probe. A cylindrical shape of the probe tip is proposed as a general concept, similar to the classic, cylindrical, 3-port probe. The main difference arises in using only two pressure signals: one from the overpressure zone on the front side of the cylinder and another, from the underpressure zone on the back side. After performing an appropriate calibration procedure, it is possible to measure the flow velocity and correct the pressure difference obtained by means of a velocity coefficient k_v. This paper also presents an analysis of the k_v coefficient uncertainty to evaluate the quality of measurements.

Keywords: pneumatic probes; probe calibration; uncertainty of measurements; velocity measurements.

1. Introduction

There has been a dynamic development of modern measurement techniques over the last several years. In particular, this concerns more sophisticated methods, such as hot wire/hot film anemometry or optical techniques like PIV or LDA. These methods have numerous advantages including the possibility of visualization of the flow field or excellent dynamic response, which enables to track temporal variations of velocity.

Nevertheless, classic pneumatic probes are still in use, offering some outstanding features, which make them irreplaceable in many applications [10]. In particular, they are easy to use and their measurement results are easy to interpret.

Among the most popular pneumatic probes are the Pitot and Pitot-static (Prandtl) probes (for 1-D measurements) [4, 8], cylindrical 3-port probes (for 2-D applications) [3, 12] or spherical 5-port probes (for 3-D applications) [2, 11]. The application of classical, standard Pitot or Prandtl probes is impossible in many cases because of a limited space where the probes are to be mounted. When measurements in closed conduits or the inner spaces of turbomachines are

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considered, installing a Pitot/Prandtl probe is extremely inconvenient, as its measuring tip is perpendicular to the stem and a relatively large space is required to mount the probe in a duct. The axial dimension of the probe tip is relatively important and hard to minimize. Additionally, the mounting slot has to be quite large to ensure the proper installation and tightness of the assembly.

Nevertheless, some types of compact, differential, pneumatic probes that can be easily installed in a duct are known from the literature. Birri and Voegtli [1] designed a 2-port cylindrical probe that they named the "cylindrical Pitot" (Fig. 1a). The probe has the shape of a long cylinder, with two small radial holes placed at a given angle to the diametric plane. The probe was used in a system monitoring the compressor mass flow rate. The aim of their work was to develop a probe that would be insensitive to the angle of incidence over a wide range of angles. Kateusz et al. [5] made extensive experimental tests of three types of probes of different shapes: 2-port cylindrical probe, S-type probe and Diamond-shape probe (Fig. 1c, d, e). These probes were tested in laboratory conditions within a range of velocities (0÷30 m/s) for different turbulence intensities and different turbulence scales.

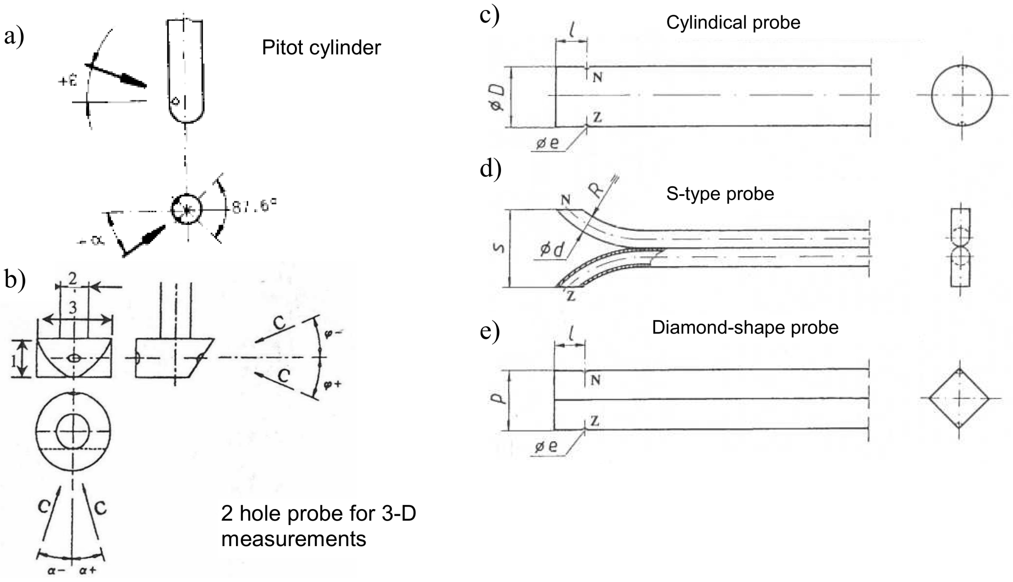

Fig. 1. Different solutions of compact 2-port pneumatic probes.

In the case of measurements in exhaust gas conduits, special attention must be paid to the problem of probe fouling, because of the presence of solid particles. Considering this, the most common solution is the application of S-type probes (Fig. 1d), because of large diameters of measuring holes, which are practically the same size as the inner diameters of pressure tubes transmitting a pressure signal to the measuring device. This feature makes these probes the most commonly employed in measurements of dust emissions [9]. Although the manufacturing technology of these probes is very simple, their aerodynamic characteristics are very sensitive to technological nuances [7].

An interesting concept of a two-hole probe for 3-D flows (cf Fig. 1b) was also given by Najdecki [6]. However, the procedure for calibrating such a probe is very complicated and time-consuming.

Considering the features and limitations of the solutions described above, a 2-port cylindrical probe has been chosen for this specific application, where restrictions concerning a limited space available for the probe installation and the number of output signals (only two signals transmitted to the differential pressure transducer) are imposed. These restrictions have shaped the concept and construction of the probe.

2. Concept and construction of probe

The probe was designed to work in a furnace for annealing steel coils (Fig. 2). Seven mixers – driven by electric motors – were distributed uniformly on the upper capping of the furnace (Fig. 2a). Their aim was to enforce circulation inside the furnace. The technological regime required that the discrepancies in velocity at the mixers' outlets were not to exceed 5%. Thus, these velocities had to be measured and controlled.

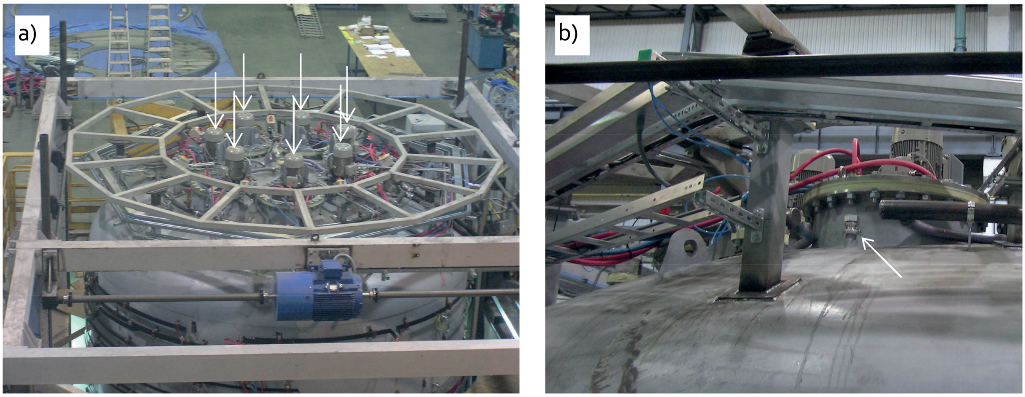

Fig. 2. General views showing the distribution of mixers on the top surface of the furnace (a) and the position of welded pipe couplers for probe mounting (b).

The application of standard Prandtl probes was impossible in this case, because of a limited space in the furnace. Due to the space restrictions, a simple solution, in the form of a cylindrical probe (Fig. 3, Fig. 5) was implemented.

A typical cylindrical probe has 3 ports, located on the front side of the sensor (Fig. 3b).

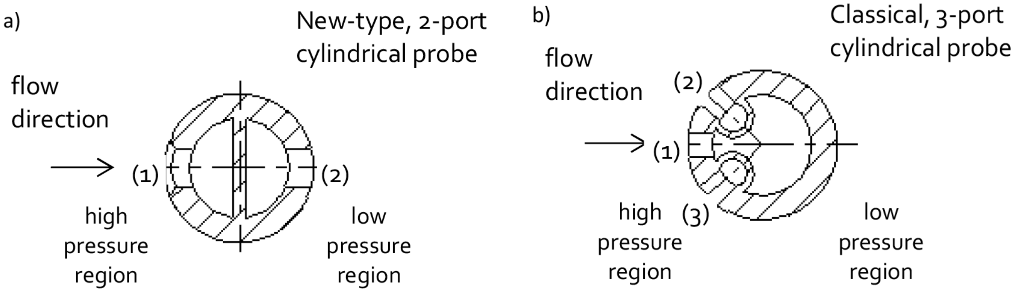

Fig. 3. Sectional views showing the location of ports in the new 2-port probe (a) and the classical 3-port probe (b).

If pressure signals from the outer ports (n° 2 and 3) are equal, the central port position corresponds to the stagnation point and it senses the total pressure of flowing fluid. By combining pressure signals from these 3 ports one can determine both the static and the total pressures and obtain information about velocity and its direction in a 2-D system [3]. However, this solution requires 3 pressure signals to be measured, whereas most data acquisition systems prefer using standard differential pressure transducers with two pressure intakes. The idea arose to sense only two pressure signals – from the front and from the back sides of the cylinder (Fig. 3a). This concept is similar to that presented in [1], however a fundamental difference concerns the position of ports. It is commonly known that the flow around a circular cylinder produces a specific pressure distribution on its surface (Fig. 4). The high pressure (overpressure) zone appears on the front side of the cylinder, whereas the low pressure zone (suction pressure) – on the back side.

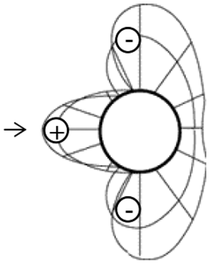

Fig. 4. Pressure distribution on the surface of a cylinder during the flow of gas around it.

If the front sensing port is positioned according to the flow direction, it will sense the total pressure p_e, expressed as:

$$p_e = p + p_d \tag{1}$$

with

$$p_d = \rho \frac{v^2}{2}, \tag{2}$$

where:

p – static pressure;
p_d – dynamic (impact) pressure;
ρ – fluid density;
v – flow velocity.

The position of the second port is chosen opposite to the first one, on the back side of the cylinder (Fig. 3a, Fig. 5), as in the cylindrical probe described in [5]. This position has its merits, but also some disadvantages.

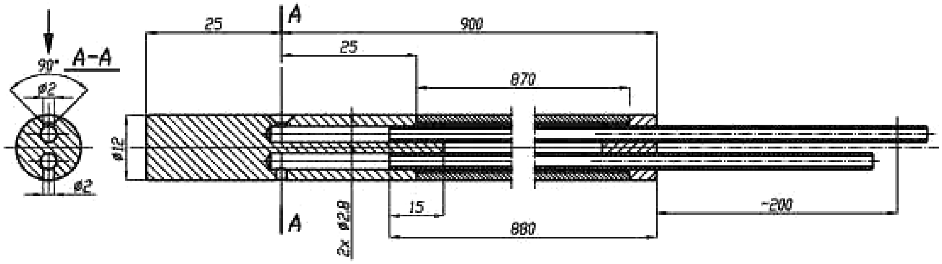

Fig. 5. A cross-sectional view of a 2-port cylindrical probe.

The suction pressure in the second port is unknown and there are no relationships which could associate it with the flow parameters. Moreover, it varies as a function of the flow velocity, and the position of the separation point is variable as well. In consequence, we are not able to link the measured pressure difference $dp = p_1 - p_2$ to the flow velocity v without performing probe calibration. This feature distinguishes this probe from the Prandtl probe, which directly uses the difference between the total and static pressures, i.e. the dynamic pressure p_d. However, in the case of the 2-port cylindrical probe, the differential pressure is bigger than the dynamic pressure $(dp > p_d)$ and this fact outweighs its disadvantages (the measuring signal is greater).

As a general concept, it was decided that the measurement procedure will be the same as for the Prandtl probe, where the following well-known relation holds:

$$v = \sqrt{\frac{2 \cdot p_d}{\rho}} = \sqrt{\frac{p_e - p}{\rho}}. \tag{3}$$

The pressure difference $dp = p_1 - p_2$, used as the output signal for the 2-port probe, is linked to the flow velocity as well. However, to satisfy the relation between the velocity and the pressure difference, a correction coefficient needs to be applied. The following equation is proposed:

$$v = \frac{1}{k_v}\sqrt{\frac{2dp}{\rho}}, \tag{4}$$

where k_v is a velocity coefficient, which should be determined experimentally during probe calibration. It may be noted, that other authors use a shape coefficient $\beta = k_v^2$ instead [5].

3. Calibration of 2-port probe

The main aim of probe calibration is to determine the k_v coefficient value. Initial studies have indicated that k_v is velocity-sensitive, and a function $k_v(v)$ needs to be determined. The influence of other flow parameters – like pressure or temperature – is deemed insignificant. The calibration procedure entails assigning the reference flow velocity v_{ref} to the measured pressure difference $dp = p_1 - p_2$. The calibration of pneumatic probes is usually carried out in a free-air jet because of blockage errors that occur in closed test sections [13, 14]. That is why a wind tunnel (TCS-2) was used for the calibration procedure (Fig. 6a).

The tunnel has two important features:

- it ensures a uniform velocity profile at the nozzle outlet (7);
- it enables direct determination of the impact pressure of the flowing gas without any additional reference probes.

The pressure inside the wind tunnel corresponds to the total pressure of the stream p_e. By relating it to the static pressure inside the free-air jet at the nozzle outlet p, which is equal to the atmospheric pressure p_0, we can directly determine the impact pressure p_d. It can then be used to calculate the reference velocity according to the formula (3). This pressure is measured by means of a water column manometer (4) – Fig. 6.

A frequency inverter (Yaskawa VS-606 V7) is applied to vary the flow velocity by changing the rotational speed of the fan (6) – Fig. 6.

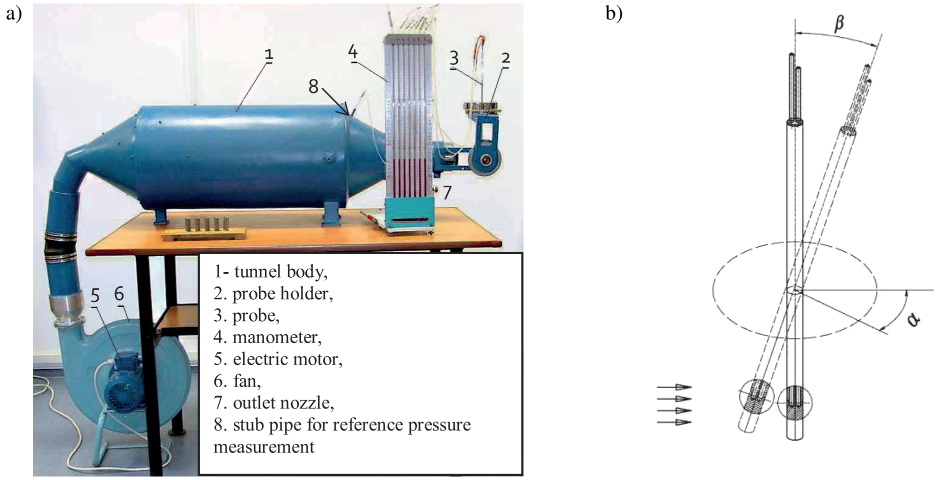

Fig. 6. A general view of the calibration wind tunnel TCS-2 (a) and definitions of rotation (α) and inclination (β) angles for the calibration procedure (b).

The main advantage of a 3-port cylindrical probe is the possibility of determining both the value and direction of velocity. A 2-port probe does not offer such a possibility. In order to obtain correct results, measurements should be performed within the insensitivity range of the probe where the output signal from the probe is independent of its angular position.

The angular characteristics of the probe should be determined in two planes (Fig. 6b):

- horizontal: the angle of rotation α is varied (the probe is turned around its axis);
- vertical: the angle of inclination β (pitch angle) is varied.

Three pressures are determined during the calibration procedure:

$p_1 = p^+$ – pressure at the front sensing point of the probe;
$p_2 = p^-$ – pressure at the back sensing point of the probe;
p_{tun} – pressure inside the calibration wind tunnel (corresponding to the total pressure p_e).

We can determine two pressure differences:

$dp = p_1 - p_2$ – differential pressure from the 2-port probe (which will be used as a measuring signal during measurements);

$dp_{tun} = p_{tun} - p_0 = p_e - p = p_d$ – overpressure in the wind tunnel, which corresponds to the dynamic pressure of the jet (where p_0 is the atmospheric pressure).

A barometer with a resolution of 0.1 kPa (Delta Ohm HD 9908T) is used to measure atmospheric pressure.

Figure 7 shows the angular characteristics of the probe, obtained for 3 different velocities: 10.5, 15.3 and 18.5 m/s. The following conclusions can be drawn:

- dynamic pressure dp_{tun}, calculated from the wind tunnel pressure, is practically constant and it can be used as the reference pressure;
- differential pressure dp from the probe varies, however, there is a large zone where it is insensitive to the probe's angular position. For lower velocities, this zone can be estimated as $\pm 17^\circ$, but it narrows for higher velocities. However, the zone of insensitivity of the probe can be considered as wide enough to proceed with measurements in straight ducts.
- in the operational range of the probe, the relation $dp > dp_{tun}$ is maintained.

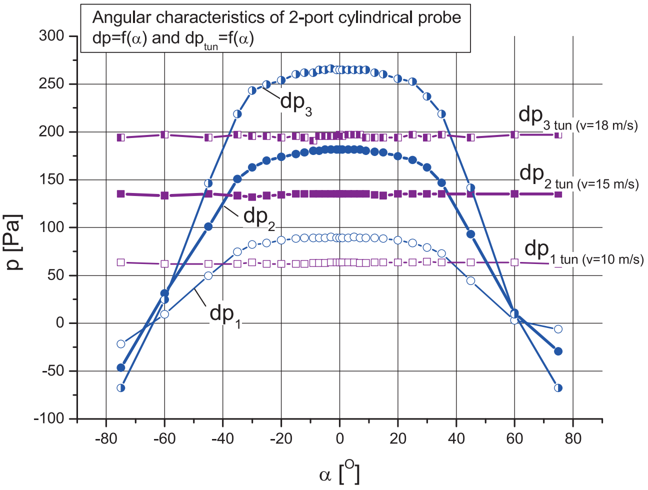

Fig. 7. Angular characteristics $dp = f(\alpha)$ and $dp_{tun} = f(\alpha)$ of the 2-port probe, for different flow velocities.

The reference velocity can be calculated from the reference dynamic pressure:

$$v = \sqrt{\frac{2 \cdot p_d}{\rho}} = \sqrt{\frac{2 \cdot dp_{tun}}{\rho}}, \tag{5}$$

where $p = \rho/(RT)$ is a gas density.

According to the above relation (5), the velocity measured by a 2-port probe can be defined as:

$$v_{dp} = \sqrt{\frac{2 \cdot dp}{\rho}}. \tag{6}$$

This velocity is not real of course (computed only), and it has no physical sense. However, it is convenient to use, as it employs the same principle as applied to the Prandtl probe (compare eq. (5) and (6)).

The aim of the calibration procedure is to relate a velocity v_{dp} to the reference one v. To link these two quantities, a coefficient k_v is defined as follows:

$$k_v = \frac{v_{dp}}{v} = \frac{v_{dp}}{v_{tun}}. \tag{7}$$

Fig. 8 shows the angular characteristics of the 2-port probe for different flow velocities. They confirm our earlier observations concerning pressures.

As far as k_v coefficient variations are considered, it can be observed that k_v is velocity-sensitive. A more detailed analysis of this issue will be presented in Section 4 of the paper.

Another set of angular characteristics is obtained by changing the probe inclination. Fig. 9 shows the characteristics of the 2-port probe for different angle β values.

The range of insensitivity for β angles is narrower than for rotation angles α and it can be estimated as ±5°. However, it can be considered wide enough given that the probe is usually mounted vertically and its alignment can be easily checked.

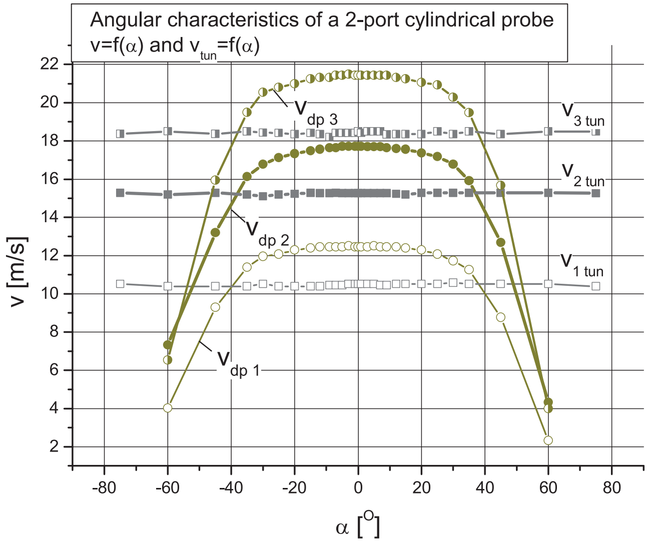

Fig. 8. Angular characteristics of the 2-port probe, for different flow velocities $v_{tun} = 10.5/15.3/18.5$ m/s.

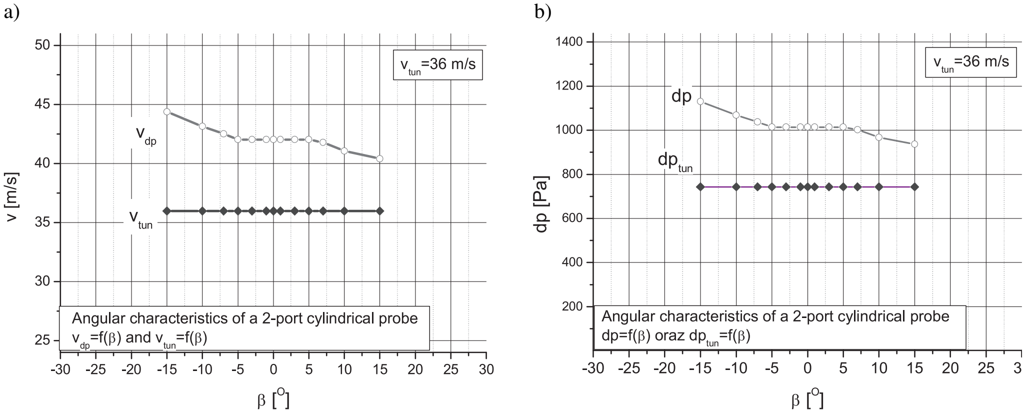

Fig. 9. Angular characteristics $v = f(\beta)$ (a) and $dp = f(\beta)$ (b) of the 2-port probe, for a flow velocity $v_{tun} = 36$ m/s.

4. Analysis of k_v coefficient characteristics

The coefficient k_v, defined by the relations (4) and (7), enables to calculate the flow velocity resulting from the differential pressure dp measured directly with the 2-port probe. Its value is determined experimentally during the probe calibration (cf. Section 3).

In order to examine the influence of the flow velocity on the k_v coefficient, additional tests were performed in an enlarged velocity field (up to 42 m/s). It should be emphasized that the k_v value results from the pressure difference dp occurring on the probe surface for a given flow velocity, hence examining this correlation is of crucial importance. Fig. 10 presents the comparison of gauge pressures dp^{+} and dp^{-} measured on the front and back sides of the probe during the calibration.

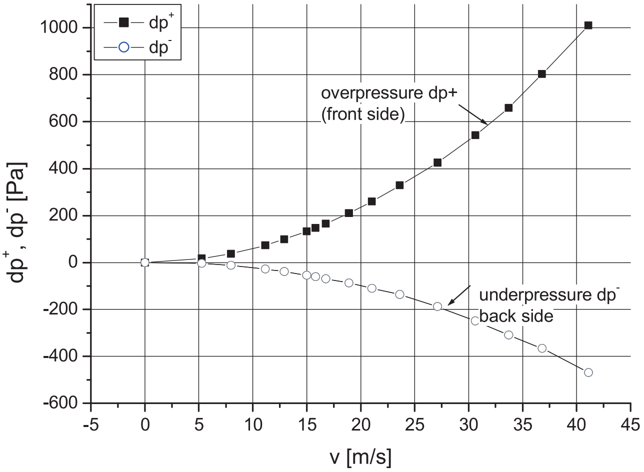

Fig. 10. Comparison of the measured and calculated gauge pressures dp^+ (at the front) and dp^- (at the back side of the probe). Results for air jet temperature $t = 24.5°\text{C}$.

The resulting pressure difference $dp = dp^+ - dp^-$ can be expressed as a function of the flow velocity v as shown in Fig. 11a. Two sets of data are presented there: v_{dp} – curves that represent the computed velocity, calculated directly from the pressure difference dp (eq. (6)), and v – the flow velocity measured during the calibration.

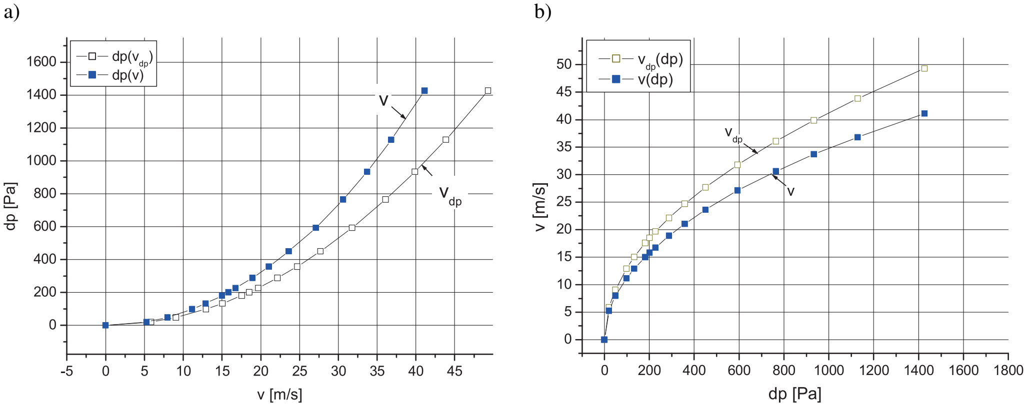

Fig. 11. Comparison of velocities v and v_{dp} in relation to pressure difference dp. Results for air jet temperature $t = 24.5°\text{C}$.

It can also be clearly seen that the numerical velocity v_{dp} is distinctly higher than the real velocity $v = v_{tun}$. This dependence is easier to demonstrate in an inversed coordinate system $v = f(dp)$ – Fig. 11b.

From a practical point of view, during measurement it is easier to use the k_v coefficient than to determine the velocity value directly from the graph $v = f(dp)$, as shown in Fig. 11b. The problem is that k_v is velocity-sensitive and the $k_v(v)$ characteristics must be determined experimentally.

Fig. 12 shows traces of $k_v(v)$ and $k_v(dp)$ functions obtained during the probe calibration. As the flow velocity v is unknown, it is easier to use $k_v(dp)$ characteristics in the measurements procedure.

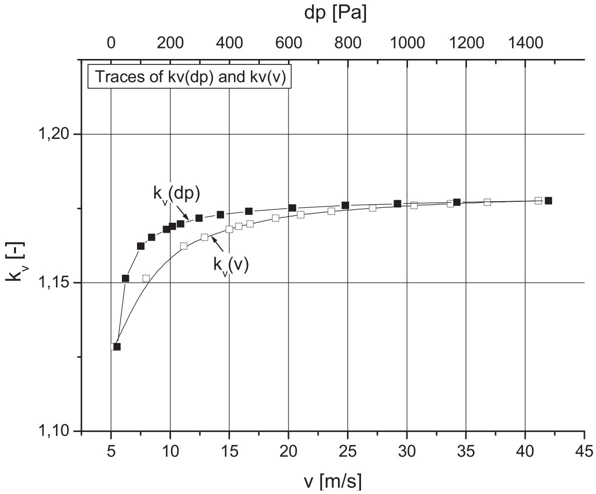

Fig. 12. Comparison of experimental characteristics $k_v = f(dp)$ and $k_v = f(v)$.
Results for air jet temperature $t = 24.5°\text{C}$.

It is worth noting that the k_v coefficient rises asymptotically and then stabilizes, so – apart from the range of low velocities – the k_v coefficient can be considered constant.

5. Accuracy of k_v coefficient

For reliable velocity measurements by means of a cylindrical probe it is necessary to establish the k_v coefficient accuracy. The accuracy determination procedure corresponds to the probe calibration method with the use of a water column manometer.

According to (7), coefficient can be expressed as:

$$k_v = \frac{v_{dp}}{v} = \frac{v_{dp}}{v_{tun}} = \sqrt{\frac{dp}{dp_{tun}}}, \tag{8}$$

$$\begin{cases} dp & = \dfrac{\rho_m g \Delta l}{i_m} \\ dp_{tun} & = \dfrac{\rho_m g \Delta l_{tun}}{i_m} \end{cases}, \tag{9}$$

where ρ_m is specific weight of the manometer fluid, g is acceleration of gravity, Δl, are respective liquid heights and i_m is a manometer ratio ($i_m = 1/\sin\theta$, where θ is a manometer inclination angle).

According to the uncertainty propagation law [15] – cf. Fig. 13:

A standard complex uncertainty of the k_v coefficient can be expressed as:

$$u_c(k_v) = \sqrt{\left(\frac{\partial k_v}{\partial dp}\right)^2 u_c^2(dp) + \left(\frac{\partial k_v}{\partial dp_{tun}}\right)^2 u_c^2(dp_{tun})} \tag{10}$$

Fig. 13. A scheme of uncertainty propagation for the k_v coefficient.

or, using a relative uncertainty:

$$\frac{u_c(k_v)}{k_v} = \sqrt{\left(\frac{\frac{1}{2}u_c(dp)}{dp}\right)^2 + \left(\frac{\frac{1}{2}u_c(dp_{tun})}{dp_{tun}}\right)^2}. \tag{11}$$

In the same way an uncertainty $u_c(dp)$ can be expressed as:

$$\frac{u_c(dp)}{dp} = \sqrt{\left(\frac{u_c(\rho_m)}{\rho_m}\right)^2 + \left(\frac{u_c(g)}{g}\right)^2 + \left(\frac{u_c(\Delta l)}{\Delta l}\right)^2 + \left(\frac{u_c(i_m)}{i_m}\right)^2}. \tag{12}$$

Assuming uncertainties $u_c(\rho_m)$, $u_c(g)$ and $u_c(i_m)$ as negligible in comparison with $u_c(\Delta l)$ we obtain:

$$u_c(dp) = dp\frac{u_c(\Delta l)}{\Delta l} = \frac{\rho_m g u_c}{i_m}(\Delta l) \tag{13}$$

and consequently:

$$u_c(dp_{tun}) = dp_{tun}\frac{u_c(\Delta l_{tun})}{\Delta l_{tun}} = \frac{\rho_m g u_c}{i_m}(\Delta l_{tun}). \tag{14}$$

During the measurements, the manometer ratio i_m value varied between 1 and 4.98 to match the manometer range to the flow velocity. As a result of this, the uncertainty $U(k_v)$ is affected (cf. Table 1).

Table 1. A list of k_v values and their uncertainties for different flow velocities.

v [m/s]	i_m [–]	$\bar{k}_v$ [–]	$u_c(k_v)$ [–]	$u_c(k_v)/k_v$ [%]	$U(k_v)$ [–]
10.5	4.98	1.160	0.015	1.3	0.030
15.3	4.98	1.169	0.007	0.6	0.015
18.5	2.51	1.172	0.010	0.9	0.020
41.3	1	1.178	0.005	1.1	0.010

Table 1 presents the k_v values and their uncertainties calculated for the tested flow velocities. The mean value of k_v coefficient is calculated within the insensitivity range of the probe. Complex standard uncertainties are calculated for a single measurement. Expanded uncertainties $U(k_v)$ [16] are calculated assuming a recovery coefficient $k = 2$ [15]. It can be observed that a k_v uncertainty band decreases with velocity. This stems directly from the fact that respective pressure differences are bigger for higher velocities and this makes measurements more accurate. Relative uncertainties do not exceed 1.5% and can be considered acceptable.

6. Experimental verification of obtained results

In order to verify the obtained results, tests in closed channels were also executed. A test rig for centrifugal blower tests is adopted in order to compare the measurement results derived from the 2-port cylindrical probe with the reference ones.

A VELOCICALC Multi Function Ventilation Meter 9565-P from TSI Inc. [17] was used as the reference probe. It used a pre-calibrated thermoanemometer probe for velocity measurements. Its main parameters are as follows:

- range: 1.27÷78.7 m/s;
- accuracy: 1.5% at 10.16 m/s;
- resolution: 0.01 m/s;
- duct size: 2.5÷1270 cm.

Both (tested and reference) probes were mounted in a Ø 150.6 mm duct, downstream of the blower. A scheme and main dimensions of the experimental setup are presented in Fig. 14. In order to vary the flow velocity, a frequency inverter is used to change the rotational velocity of the electric motor driving the shaft of the blower.

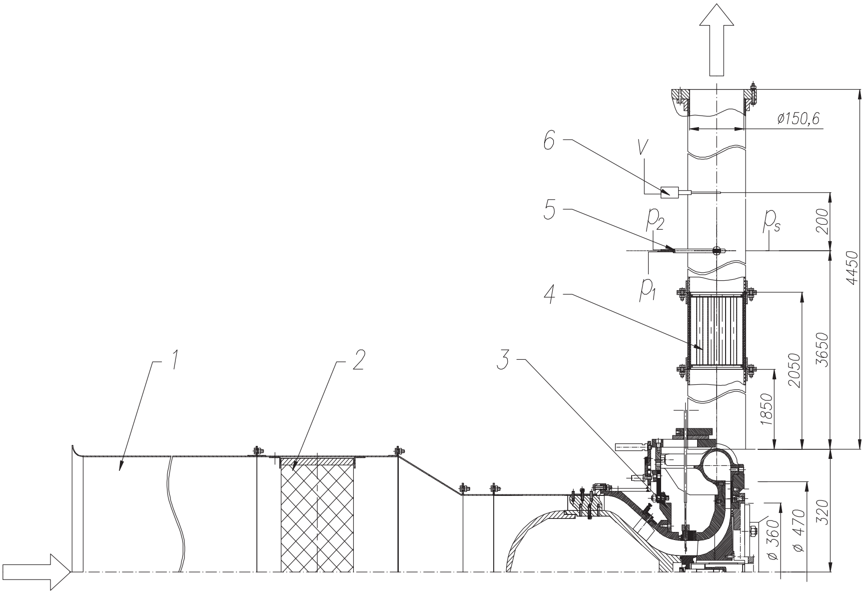

Fig. 14. A test rig for velocity measurement: 1 – inlet duct, 2, 4 – flow straighteners, 3 – centrifugal blower, 5 – 2-port cylindrical probe, 6 – reference probe (TSI 9565-P).

The result of these comparative tests are presented in Fig. 15.

To calculate the flow velocity on the basis of the measured pressure difference dp, the approximation of $k_v(dp)$ function is made by means of the following relation:

$$k_v = e^{\left(a + \frac{b}{dp+c}\right)} \tag{15}$$

with: $a = 0.164$; $b = -1.62$ Pa and $c = 17.34$ Pa.

A slight difference can be observed between flow velocity values obtained from the 2-port probe and the TSI thermoanemometer. This difference does not exceed 5% and there are several possible reasons for this discrepancy. One of the most probable is different conditions of calibration and measurement: the 2-port probe was calibrated in a free-stream jet whilst the measurements were performed in a closed duct, where blockage phenomena may occur.

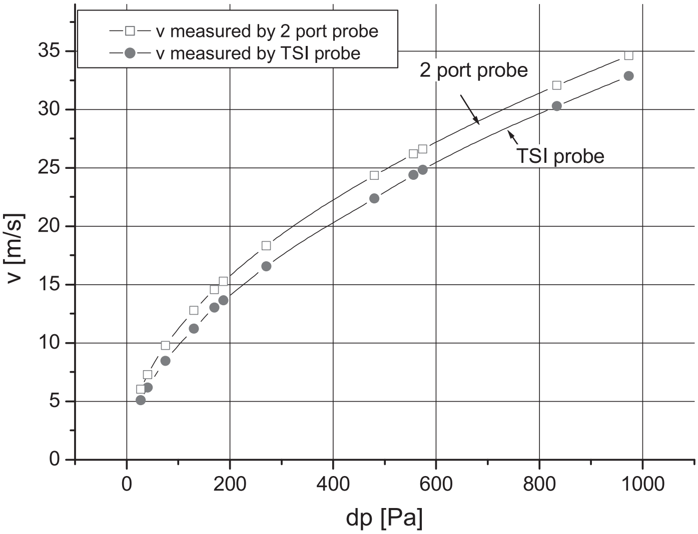

Fig. 15. Comparison of measurement results in a closed duct.

Taking into account a cylindrical probe diameter $d = 12$ mm, compared with the duct diameter $D = 150.6$ mm, the resulting d/D ratio is equal to 8%. Different guidelines concerning the recommended value of this ratio can be found in the literature. Flow Kinetics recommends the d/D ratio to be less than 3% for total pressure probes [18]. United Sensor Corporation [19] advise, that for Pitot-static probes, readings should not be taken closer to a boundary than 5 tube diameters (and 10 tube diameters is safer). These recommendations correspond to the ratio d/D in a range of 5÷10%. Nevertheless, it seems that for relatively low Reynolds and Mach numbers existing during the tests, the blockage effects do not seem to be significant. The differences in flow structures and turbulence levels will probably have a stronger impact as the flow separation on the back side of the probe is very sensitive to any instability. The results of extensive experiments by Kateusz et al. [5] show the impact of turbulence intensity and turbulence scale on the aerodynamic characteristics of similar probes. The differences in design of both test rigs seem to be crucial in this aspect. Calibration is performed in a free-air jet, at the outlet of the wind tunnel (Fig. 6a). A large capacity of the tunnel body, together with the presence of flow straighteners inside it, imply that the turbulence intensity is rather low (the authors estimate it to be not bigger than 5%). Moreover, the wind tunnel and the probe are isolated from mechanical vibrations of the system motor-fan by elastic tubing. In the case of the closed-duct measurements, even if flow straighteners are applied, a vibration level is much higher and vibrations are propagated along the metallic pipelines to the probe, enhancing the flow separation. Nonetheless, the coincidence of results obtained with these two different methods and the results' stability show a potential of the 2-port probe for its applications in real installations.

7. Conclusions

A new type of compact, space-saving, cylindrical, 2-port, pneumatic probe is proposed as a device for velocity measurements. This probe has two main advantages:

- it is simple to handle and easy to mount inside a duct or other object (for example, it can be used between blade rings in multistage turbomachines of different kinds for velocity measurements);
- it requires only two pressure signals for determining velocity – this can be achieved with a typical differential pressure transducer, involving a relatively small amount of data processing.

The results of experiments showed that the range of insensitivity of the probe (the range of angles in which the angular position of the probe is irrelevant for measurement results) is quite large and that it can be estimated as ±9° for the rotation angle and ±5° for the inclination angle (pitch angle).

This paper demonstrates how to relate the flow velocity to the differential pressure signal dp, by means of a velocity coefficient k_v, which must be determined experimentally. This coefficient is velocity-sensitive; however, it stabilises rapidly and can be considered constant in a wide range of velocities.

Based on the calibration results, control measurements in a closed duct were performed, with the use of a TSI thermoanemometry probe. The velocity difference value in the entire range of velocities (5–35 m/s) did not exceed 5%.

Probes of this type are simple and efficient devices for velocity measurements in 2-D layouts and can be applied to different gases in a wide range of pressure, temperature and velocity values.

It seems advisable to perform more advanced experiments, regarding the turbulence parameters, which may have a substantial influence on the phenomena of flow separation in the probe surface.

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