EXPERIMENTAL RESEARCH ON VELOCITY PROFILES IN SELECTED FLOW SYSTEMS

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Abstract: A problem of measuring of velocity profiles with the use of a fully automated test stand is presented in this paper. Due to the installed measurement equipment and various software alternatives it is possible to assess the inlet effect and distribution of velocities in the vicinity of averaging Pitot tubes in order to determine the phenomena occurring in their vicinity (recirculation, main stream direction) and verify the numerical models of turbulence. Due to the stream recirculation in the vicinity of the probes tested in a wind tunnel, a two-way probe was used instead of a Pitot tube. A linear module with a stepper motor formed an integral part of the measurement system whereby it was possible to determine the position of the measurement probe with a precision of 0.1mm. The measuring anemometer location, the possibility of adjusting the stream mean velocities and data acquisition were established by means of an original program.

As far as the research in pipelines is concerned – the resulting characteristics allow the uncertainty of measurement to be precisely determined, which should be accounted for during the determination of air fluxes at locations which are not included in the technical documentation of a flowmeter.

Keywords: velocity profiles, air flow measurement, closed conduits, automated test stand, differential pressure flowmeter

1. Introduction

Velocity profiles of a flowing fluid play an important role during the selection of the installation point of a flowmeter. A variety of ways to measure the velocity profile using the ultrasonic method [1–3], the impact probe [4] or the LDV method [5] are described in the literature. Depending on the flow system configuration the literature refers to various locations for the flowmeter installation [6–9]. A particular role in this respect is given to local obstacles which cause a reversal of the flow direction (e.g. elbows, valves, throttles, changes in the pipeline cross-section, tee joints) as they lead to disturbance in the velocity profiles. Paper [8] presents cases of axially symmetrical deformation, asymmetry
and asymmetry with flow disturbance areas. Figure 1 illustrates the case of flow through a bend which causes asymmetrical deformation of the velocity profile.

Flowmeters which are sensitive to the velocity profile deformation have to be installed at a relatively large distance from the obstacle (Table 1) [6, 7].

However, in metrological practice we often have to deal with the need to shorten the distance between the obstacle and the flowmeter due to the specific characteristics of an installation. In the case when the application of a flow straightener is unjustified due to economic or metrological considerations, the measurements of velocity profiles can be taken at selected installation locations with the aim of assessing the effect of flow deformation due to the installation of a flowmeter [8, 10]. Due to the unexpected distribution of the fluid velocity it is necessary to take measurements at a considerably larger number of points than stipulated in the standard [11]. Such studies are possible on an automated and original laboratory stand.

2. Test stand

The test stand was prepared in a manner to enable measurements on various diameters of pipelines (DN 110 to DN 315) with an arbitrary angle in relation to the pipeline axis. Due to the installed measurement equipment and various software alternatives it was possible to assess the inflow effect, flow behind local obstacles (elbows, valves, diffusor, confusor) and distribution of velocities in the vicinity of Flow Averaging Tubes (FAT) in order to determine the phenomena occurring in their vicinity (recirculation, main stream direction) and verification of the numerical models of turbulence.

It was also possible to determine the mean velocity on the basis of a program accounting for a number of measurement points, their location in relation to the axis and the local velocities. For pipeline tests the measurement system was installed with a system of variable ambient condition compensation (measurement of temperature and absolute pressure). Due to the compact structure it was possible to perform measurements not only in laboratory conditions, but in real industrial facilities as well. A linear module with a stepper motor (Figure 2)
Table 1. Examples of average lengths of pipelines before and after FAT for different flow systems [7]

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<th>System with or without flow straightener</th>
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formed an integral part of the measurement system allowing the position of the measurement probe (Pitot tube or two-direction probe) to be determined during the measurements with a precision of 0.1mm.

The measuring anemometer location, the possibility of adjusting the stream mean velocities and data acquisition were established by means of an original program (independently for each case) operating in the LabVIEW environment (Figure 3). More information about the program and the tests stand can be found in [12].

The program determines the velocity profiles for selected mean velocities in the range from 10 to 26m/s. The operator decides about the measurement uncertainty and the resolution of measurements by providing an adequate parameter associated with the duration of the measurement by means of a turbine flowmeter. The default value is set at 0.01m/s. The measurement of mean velocity by means of a turbine flowmeter located at a certain distance makes a reference to the
Figure 2. Integral part of automated test stand for velocity profile measurement for pipeline tests: (a) flow past 90-degrees elbow, (b) inflow effect with visible turbine flowmeter in background

Figure 3. Example of velocity profile controlled by computer program behind segment elbow (DN 160)

place where the velocity profile is measured (correction of air density) by adopting constant measurement of the absolute pressure and temperature. The total uncertainty of the measurements conducted on the test stand was determined in detail in [13] to be 0.64% of the measured value. The maximum uncertainty of the measured value of variables by the equipment is equal to:

- the turbine flowmeter < 0.5% of the measured value;
- the differential pressure transducer < 0.075% of the measured value;
- the absolute pressure transducer < 0.1% of the measured value;
- the thermometer < 0.2% of the measured value;

respectively.

The program operating parameters having been determined, the centrifugal blower motor (with the maximum volumetric flow rate of 12000 m$^3$/h) regulates the flow velocity by means of an adaptive algorithm depending on the ambient conditions (pressure and temperature) via a frequency transducer. When the flow
velocity has gained stability, the measurement of the velocity profile starts by periodic displacements of the Pitot tube installed in the linear module holder (Figure 2) to the subsequent predefined spots along the pipeline diameter. The measurement series for each mean velocity follow in turn by automatically increasing the flow velocity until the final measurement series is complete when the blower motor can come to a stop. The measurement results are presented online in the form of a chart (Figure 3) and recorded in a text file.

The signal in both directions is transmitted by means of measurement cards integrated in the CompactDAQ system (Figure 4).

![Figure 4. Data Acquisition System CompactDAQ](image)

The specialized data acquisition system CompactDAQ (Figure 5) is equipped with the following components:

- the NI 9217 module for resistance measurement (temperature measurement);
- the NI 9203 module with analog current input channels (4–20mA) to control the absolute pressure transducer, differential pressure transducer, barometer;
- the NI 9265 module with analog current input channels (4–20mA) to control the electric motor rotation (frequency converter);
- the NI 9205 module with counter input channels to control the turbine flowmeter;
- the NI 9403 module with digital input/output channels to control the stepper motor and limit sensors.

The measurements conducted in a wind tunnel (Figure 5) make it possible to determine the velocity profiles around and behind a flowmeter (or another solid body).

The velocities in the area of measurement range from 6 to 36 m/s. The dimensions of the test cross-section are equal to 300 × 300 mm. The equipment used in the tests is presented in Figure 5b. The mean velocity is measured by means of a Pitot tube [14, 15] located at the bottom of the channel where, additionally, an absolute pressure transducer and a stub pipe for measuring the static pressure are found. The top part contains a removable installation plate with the examined
Figure 5. Wind tunnel tests (flow around a body): (a) linear module with stepper motor and tested flowmeter, (b) overall view of test section with appropriate equipment

tubes located thereon. There are crosswise grooves every 30mm, over the length of 200mm, sealed with a silicon plate with the thickness of 3mm behind the plate (from the side of the outlet) (Figure 5a). As a result, it is possible to measure the velocity profile at any distance from the examined shape in the range of up to 500mm. The rear part of the tunnel contains a Pt-100 thermometer. The measurement uncertainty of such a device has been discussed above, while the uncertainty of the measured mean velocity for a Pitot tube is estimated to be equal to 1%.

Due to the stream recirculation in the vicinity of the probes tested in the wind tunnel, a two-way probe with the diameter of 2mm (one behind the other) was used instead of a Pitot tube (Figure 6).

The two-directional probe was calibrated before application for determination of velocity profiles and the mean value of the flow coefficient $K$ was determined to be 0.860. This value was adapted in the software together with other parameters for measurements of local velocity in the concordant and discordant directions of the incoming flux. The interface of the computer program is similar to the one presented in Figure 3, whereas the program code is less complex due to a different manner of measuring mean velocities in the channel.

3. Experimental results

The experiments were conducted in a pipeline, $D = 152$mm in diameter and in a wind tunnel. The tests in the pipeline were aimed at indicating the effect of local disturbance on the velocity profiles in selected places in an installation. This information was subsequently applied for the optimization of the flowmeter installation point (e.g. vertical or horizontal plane). Figure 7 illustrates the velocity profiles for a single 90° elbow with the curvature radius of $1.5D$. The presentation focuses only on selected characteristics due to the need of keeping the charts clear. The location of the measurement points was set at 2mm. The broken line marks the velocity profiles in the cross-sections close to the bend – these locations are discouraged by manufacturers of flowmeters (Figure 1).
A conclusion can be drawn from the charts that the disturbance to the profiles behind the elbow displays the characteristics of axial symmetry specific for the horizontal plane (in accordance with the data in Figure 2a), whereas, for the vertical plane, the velocity tends to increase in the close vicinity behind the bend (i.e., in the bottom part of the chart). These characteristics additionally indicate that the velocity profile is symmetrical in both cases at the distance of $12D$ and it is completely developed.

A subsequent step involved tests aimed at assessment of metrological parameters of flowmeters with flow averaging Pitot tubes installed in places of deformed velocity profiles (therefore, they are discouraged by manufacturers). The characteristics of the flow coefficient gained in this way the measurement uncertainty resulting from the application of a flowmeter at a specific place in the installation, where the velocity profile is disturbed [10].

Additional testing of the inflow effect was performed also for the case when the velocity profile was determined for the internal diameter of 152mm.
Figure 7. Velocity profiles behind 90° elbow at average velocity \( w = 18 \text{m/s} \): (a) horizontal plane, (b) vertical plane

The velocity profiles were determined for the lengths from \( 2D \) to \( 42D \) for the mean flow velocities of \( 10 \text{m/s} \), \( 14 \text{m/s} \), \( 18 \text{m/s} \), \( 22 \text{m/s} \) and \( 26 \text{m/s} \). The chart (Figure 8a) presents a selection of the registered characteristics which indicate how the velocity profile is formed in a straight pipe. The aim of the testing was to indicate the minimum section of a straight pipe which was required for the formation of the velocity profile in which the measurement of the flow by means of any flowmeter would be possible with the uncertainty at a preset level. Just as in the case of the measurements behind an elbow, the subsequent step involved the testing of selected structures of flow averaging tubes with regard to the additional measurement uncertainty in the selected spots of the installation.

Additionally, the effect of inflow resistances at the inlet of the channel on the characteristics of the velocity profiles at the distance of \( 35D \) from the inflow was investigated. This involved 4 cases: a pipe without any additional elements at the inflow, a confusor with a steel grid of \( 1 \times 1 \text{mm} \) and fabric filters with low and small density (Figure 8b).

It can be clearly seen in the chart that the steel grid plays the role of a vortex generator and the course of the characteristics becomes irregular while the fabric filter tends to smoothen the asymmetrical velocity profile due to an increase in the pressure drop at the inlet. The application of a fabric with higher density leads to further smoothening of the characteristic, axial symmetry of the course and a slight decrease in the ratio of the mean velocity to the maximum velocity.
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Figure 8. Inflow effect at average air velocity \( w = 18 \text{m/s} \) \((D = 152 \text{mm})\): (a) velocity profile formation along pipe, (b) influence of different flow resistances at inflow at the distance of 20\(D\)

Additionally, for the purposes of comparison, the velocity profile is presented for the theoretical data based on the formula [16]:

\[
V = V_{\text{max}} \left(1 - \frac{r}{R}\right)^m
\]  

(1)

where \(V\) is the local velocity, \(V_{\text{max}}\) – the velocity in the pipeline axis, \(r\) – the actual radius, \(R\) – the internal radius of the pipeline, \(m\) – the exponent relative to the number \(Re\) and the pipeline roughness.

The testing in the wind tunnel was applied for the determination of the effect of the cross-section of the probe on the velocity profiles of the air for various mean velocities: \(w = 10\text{m/s}, 18\text{m/s}\) and \(26\text{m/s}\). Such action was aimed at indicating the advantages of the flow averaging Pitot tubes, one of which consisted in their negligible effect on the flowing fluid. This is associated with the quick restoring of the initial velocity profile for the case of the majority of the cross-sections of the probes available in the market. 5 different cross-sections of Flow Averaging Tubes were investigated. The specific dimensions of these probes are shown in Figure 9.

The charts presented in Figures 10–14 contain broken lines which represent the spots where velocity profiles were measured, and „0” marks the rear part of the probe’s cross-section. The colors of the measurement lines are identical with the colors used in the characteristics of the velocity profiles. If a characteristic overlaps with the line, it denotes a value equal to 0, the characteristic below the line means a negative velocity (flow reversal) and above the line – denotes a positive value. The distance from the respective broken line forms the measure of the velocity of a medium. For instance, for the line „40” and mean velocity of 26\text{m/s} the axial velocity is calculated by subtracting the location of the line (32–40) from the...
location of a point on the chart, thus receiving the result: $-8\text{m/s}$, and the highest velocity ($73-40$) is $33\text{m/s}$. The presented velocity profiles, in accordance with the notes in the charts, refer to the components of the velocity vector in the direction of $y$ axis. The measurement points were registered over a width of $200\text{mm}$ and the distance between the adjacent points was equal to $2\text{mm}$.

Figure 10 presents local velocity distributions behind the two-profile probe and between the profiles. Air velocity increases in the contraction, thus leading to a considerable static pressure drop along the side of the profile to the right (it gives the measurement signal for the determination of the flow rate by this probe). It was purposeful to apply a profile with a diverse cross-section (a recess along the left-handed profile) in order to cause the flow to transfer towards the right-side profile. This is illustrated by the characteristics of the velocity profiles between the profiles based on a larger number of measurement points taken every $0.5\text{mm}$.

A probe with a circular diameter (Figure 11) leads to inconsiderable disturbance of the liquid stream. A more intensive recirculation zone in the close vicinity of the streamlined profile can be noted with an increase in the mean velocity.

The probe with a quadratic cross-section (Figure 12) leads to a considerable pressure drop due to its shape and leaves a wide marked aerodynamic shade effect. A higher mean velocity results in the occurrence of recirculation just behind the streamlined shape, which did not occur for the case of the velocity $w = 10\text{m/s}$.

**Figure 9.** Tested probe cross-sections and particular dimensions: (a) square, (b) two-profile, (c) streamlined, (d) circular, (e) double-circular
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Figure 10. Two-profile probe: (a) mean velocity $w = 10\, \text{m/s}$, (b) mean velocity $w = 26\, \text{m/s}$

Figure 11. Cylindrical probe: (a) mean velocity $w = 10\, \text{m/s}$, (b) mean velocity $w = 26\, \text{m/s}$

Figure 13 illustrates the flow along a probe based on two cylinders situated one behind the other, while the ratio of their diameters is equal to $2:1$. Such a solution offers a number of advantages: smaller vibrations in comparison to the cylindrical probe, easier separation of the averaging chambers and a flat characteristic of the flow coefficient. The velocity profiles only inconsiderably diverge from those registered behind the cylindrical probe (Figure 11).

The probe with a streamlined cross-section (Figure 14) leads to the smallest disturbance of the velocity profiles in comparison to the previous cross-sections due to the side walls situation at an angle of $14^\circ$ in relation to the incoming stream. It follows from the charts that the recirculation of the streams occurs in the narrow area behind the probe – between 3 and 15 mm.
The resulting characteristics present results averaged in time. The phenomena occurring in the vicinity of the streamlined profiles are variable in time and of a periodical nature. Due to the considerably large velocities, it is difficult to register the behavior of liquid streams in a very short time experiment. The available measurement equipment makes it impossible to register the phenomena during the streamlined flow through the probes. There is a considerable number of questions which arise during the numerical simulations of flow using various turbulence models, e.g. pressure distribution, points of separation of the wall layer, intensity of turbulence, frequency in which vortices tend to separate.
The criterion to be applied for the validation of an adopted model will be the one based on the velocity profile derived from experimental research and numerical simulations.

4. Results of numerical simulations

The experimental research regarding flow past solid bodies can be related to the results of numerical simulations in order to determine the validity of the available turbulence models with regard to specific cross-sections of flow averaging probes. Due to the undertaken scope of the research this part is considerably abbreviated by focusing only on the presentation of the results. The testing involved flow systems, treating them as phenomena on a plane (2-D) in the ANSYS FLUENT program [17, 18] during the inflow of air stream with a plane velocity profile, if it corresponded to the conditions of the research conducted in the wind tunnel. Considerable qualitative conformity was obtained for all cases. It was remarked that the smallest conformity was achieved for the case of the two-profiled probe. The testing was performed on a structural mesh by application of the available turbulence models and the best results were achieved for the \( k-\omega \) model. Figure 15 presents examples of the results of a numerical simulation of a two-profile probe. This probe offers a local resistance to the air stream, dashing it away in the rear part; thus, causing alternate vortices on the one and the other side in the aerodynamic shade of the profiles.

The streamlined flow around the cylindrical probe generates von Kármán’s vortex street, which, after statistical averaging, takes the form presented in Figure 16. The statistical distribution maps indicate the qualitative and quantitative conformity of the resulting flow maps.

The presented velocity distribution maps indicate an overview of the course of the phenomena occurring in a given investigated profile. The applicability of a given turbulence model can be unambiguously assessed by reference to the
Figure 15. Examples of numerical simulation results for two-profile probe for inflow mean velocity \( w = 18 \, \text{m/s} \): (a) contours of mean velocity magnitude, (b) contours of mean \( x \) velocity, (c) velocity vectors

previously presented results of experiments. Due to the variety of characteristics in the chart, the graphical comparison (Figure 17) was not possible on a single chart. The velocity profiles are similar to those obtained in the experiments.

A conclusion can be made from the characteristics that the numerical calculations of the velocity profiles in the fluid recirculation area and intensive vortices are difficult to perform. It is commonly the case that the only source which can ensure conformance between the results can be offered by 3-D simulations using an LES model. It is problematic due to the large CPU effort required, which results from the application of extremely dense meshes and the unsteady nature of the investigated phenomena.

5. Conclusions

The presented fully automatic measurement stand offers a possibility of recording the velocity profiles on the basis of a large number of measurement points set at a distance of 0.1mm from one another. The linear model is capable of co-operation with a Pitot tube, a two-direction probe or any other device which takes the measurement of the local velocity (laser flowmeter, thermal flowmeter).
Figure 16. Examples of numerical simulation results for cylindrical probe cross-section for inflow mean velocity $w = 18 \text{m/s}$: (a) contours of mean velocity magnitude, (b) contours of mean $x$ velocity, (c) velocity vectors.

Figure 17. CFD-based $x$-velocity component distribution at mean velocity $w = 20 \text{m/s}$ behind: (a) two-profile probe, (b) circular cross-section probe.
The research conducted on pipelines offers a valuable insight into the plane (horizontal, vertical) and minimum distance between the obstacle and the flowmeter. The presented velocity profiles indicate clearly that it is possible to install a flowmeter behind the elbow at a distance which is smaller than the distance required by the manufacturer without any additional uncertainty of measurement when certain corrections have been accounted for [10].

The measurements of the velocity profiles in flow averaging probes installed in a wind tunnel reveal the advantages of the averaging Pitot tubes. These include a small pressure drop caused by them and quick restoring of the velocity profile in the pipe section behind the probe. It is possible to conclude for the majority of the presented cases that the original velocity profile is almost completely restored for the distance of 100mm.

The results of simplified numerical simulations presented in the paper indicate the opportunities offered by the numerical fluid mechanics with regard to determining velocity profiles in an arbitrary place of the flow system by means of a method which is alternative to experiments. The conformity between the experiments and numerical simulations is satisfactory; however, there is a need to analyze all the available turbulence models (just as in [19]) in order to eliminate the error resulting from the imprecise calculation of the recirculation zones of the flowing media.

The extension of the existing system is envisaged with an aim of conducting measurements in quadratic ducts by application of an additional linear model which realizes the feed in the perpendicular line. As a result there is a possibility of performing measurements of the velocity field over the entire cross-section of the channel in spots of disturbed flow. The comparison of such data with the results obtained in numerical simulations will make it possible to precisely determine the applicability of the selected calculation methods applying 3-D modeling.

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