EXPERIMENTAL RESEARCH ON VELOCITY PROFILES IN SELECTED FLOW SYSTEMS

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1. INTRODUCTION

Velocity profiles of a flowing fluid play an important role during the selection of the installation place of a flowmeter. In the literature we have to with a variety of ways to measure velocity profile using ultrasonic method [1, 2, 3], impact probe [4] or LDV method [5]. Depending on the configuration of a flow system the literature refers to various locations for flowmeter installation [6, 7, 8, 9]. Particular role in this respect is given to the local obstacles which cause reversal of the flow direction (e.g. elbows, valves, throttles, changes in pipeline cross-section, tee joints) as they lead to disturbance in the velocity profiles. Paper [8] presents the cases of the axially symmetrical deformation, asymmetry and asymmetry with areas of flow disturbance. Fig. 1 illustrates the case of flow through a bend which causes asymmetrical deformation of the velocity profile.

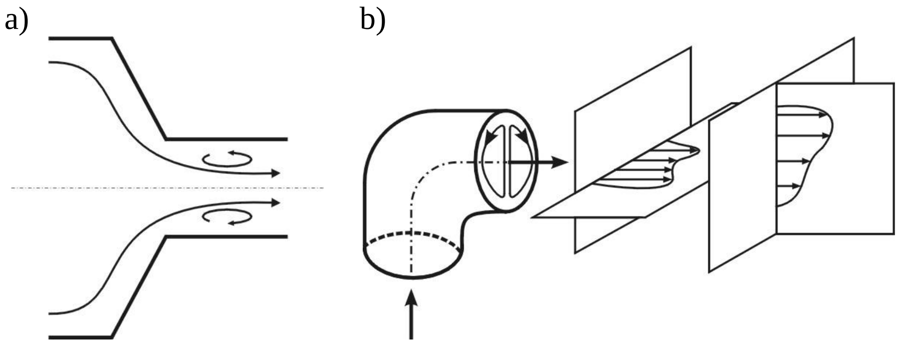
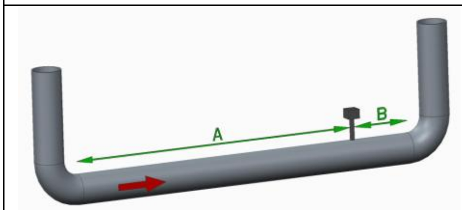
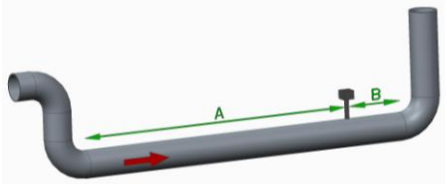
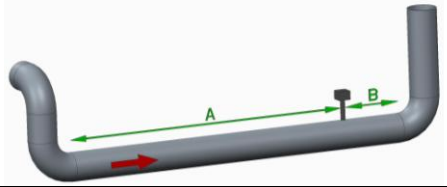
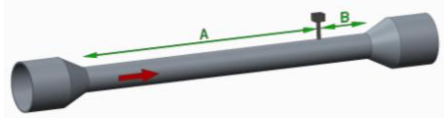
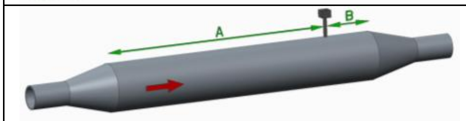
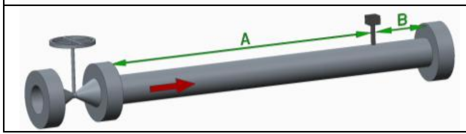


Fig. 1. Velocity profile deformation: a) axisymmetric – confusor, b) asymmetric – single elbow [8].

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

Tab. 1. Exemplary average lengths of pipelines before and after FAT for different flow systems [7].

System	L/D		
	A		B
	with	without	with or without
	flow straightener		
	12	15	6

	12	24	6
	12	42	6
	12	18	6
	12	27	6
	12	45	6

However, often in metrological practice we have to do with the need to shorten the distance between the obstacle and the flowmeter due to 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 undertaken in selected installation locations with an 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 undertake measurements in considerably larger number of points than it is 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 axis of the pipeline. Due to the installed measurement equipment and various alternatives of software use it is possible to assess the inflow effect, flow behind local obstacles (elbows, valves, diffusor, confusor) and distribution of velocities in the vicinity of the Flow Averaging Tubes (FAT) in order to determine the phenomena occurring in their vicinity (recirculation, direction of the main stream) and verification of the numerical models of the turbulence.

It is also possible to determine the mean velocity on the basis of a program that accounts for the 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 realize measurements not only in laboratory conditions, but in real industrial facility as well. A linear module with a stepper motor (Fig. 2) formed an integral part of the measurement system, which makes it possible to determine the position of the measurement probe (Pitot tube or two-direction probe) during measurements with the precision of 0.1 mm.

a) b)

Fig. 2. An 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.

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

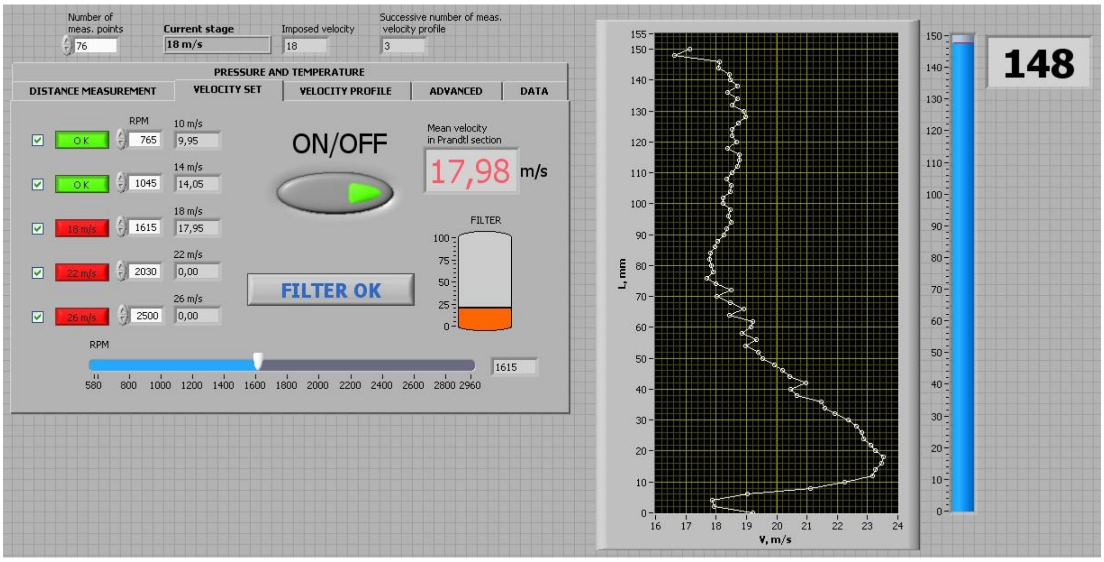


Fig. 3. An exemplary computer program controlled velocity profile behind the segment elbow (DN 160).

The program works by determining velocity profiles for selected mean velocities in the range from 10 do 26 m/s. The operator decides about the measurement uncertainty by and 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. By adopting constant measurement of the absolute pressure and temperature – the measurement of the mean velocity by means of a turbine flowmeter located at a certain distance makes a reference to the place where the velocity profile is measured (correction of air density). 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 are equal to, respectively:

– turbine flowmeter <0.5% measured value,
– differential pressure transducer <0.075% measured value,
– absolute pressure transducer <0.1% measured value,
– thermometer <0.2% measured value.

After the determination of the operating parameters of the program the motor of the centrifugal blower (with the maximum volumetric flow rate of 12 000 m^3/h) regulates flow velocity by means of adaptive algorithm depending on the ambient conditions (pressure and temperature) via a frequency transducer. After flow velocity gains stability the measurement of the velocity profile starts by periodic displacements of the Pitot tube installed in the holder of the linear module (Fig. 2) to the subsequent predefined spots along the diameter of the pipeline. The measurement series follow in turn for each mean velocity by automatic increasing 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 (Fig. 3) and recorded in a text file.

The transmission of the signal in both directions is realized by means of measurement cards integrated in the CompactDAQ system (Fig. 4).

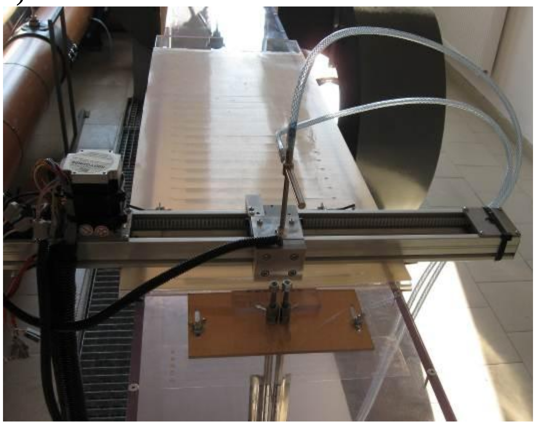
Fig. 4. Data Acquisition System CompactDAQ.

The specialized data acquisition system CompactDAQ (Fig. 5) is equipped with following components:

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

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

a)



b)

Fig. 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.

The range of the velocities in the area of the measurement ranges from 6 to 36m/s. The dimensions of the test cross-section are equal to 300×300mm. The equipment used in the tests are presented in Fig. 5b. The measurement of the mean velocity is performed by means of a Pitot tube [14, 15] located at the bottom of the channel where, additionally, absolute pressure transducer and stub pipe for the measurement of the static pressure are found. The top part contains a removable installation plate with the examined tubes located on it. Behind the plate (from the side of the outlet) there are crosswise grooves over the length of 200 mm every 30 mm, sealed with a silicon plate with the thickness of 3mm (Fig.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 is estimated for a Pitot tube to be equal to 1%.

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

a) b)

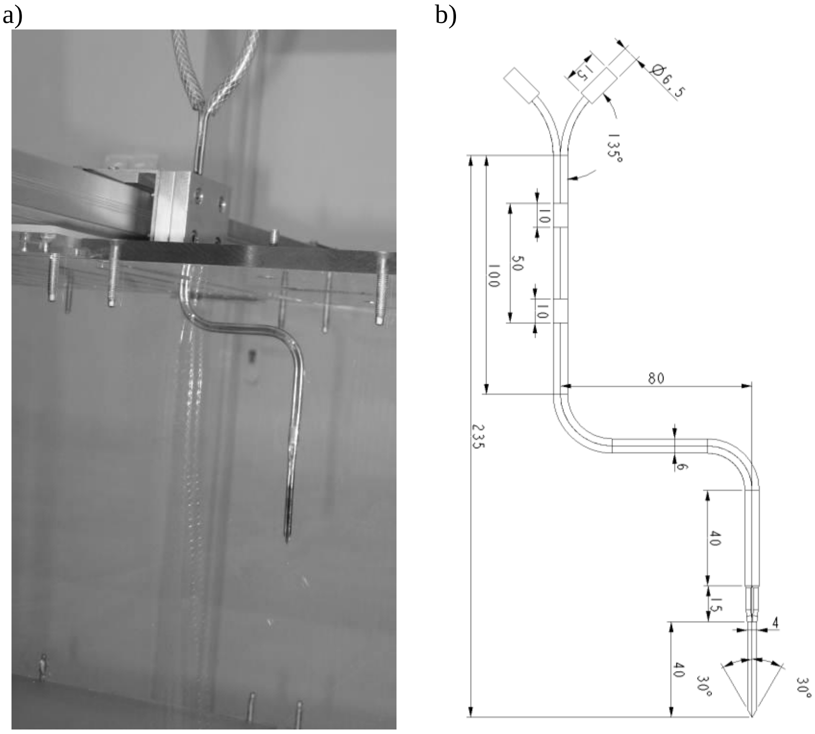


Fig. 6. Two-direction probe for velocity profile determination during wind tunnel tests: a) probe mounted in linear module over wind tunnel control section, b) characteristic dimensions.

The two-directional probe was calibrated before its application for determination of the 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 which enable 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 Fig. 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 undertaken in a pipeline with the diameter of D=152 mm and in a wind tunnel. The tests in the pipeline were aimed at indication of 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 installation place of a flowmeter (e.g. use of vertical or horizontal plane). Fig. 7 illustrates the velocity profiles for a single 90º 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 2 mm. The broken line marks the velocity profiles in the cross-sections close to the bend – these locations are discouraged by the manufacturers of the flowmeters (Fig. 1).

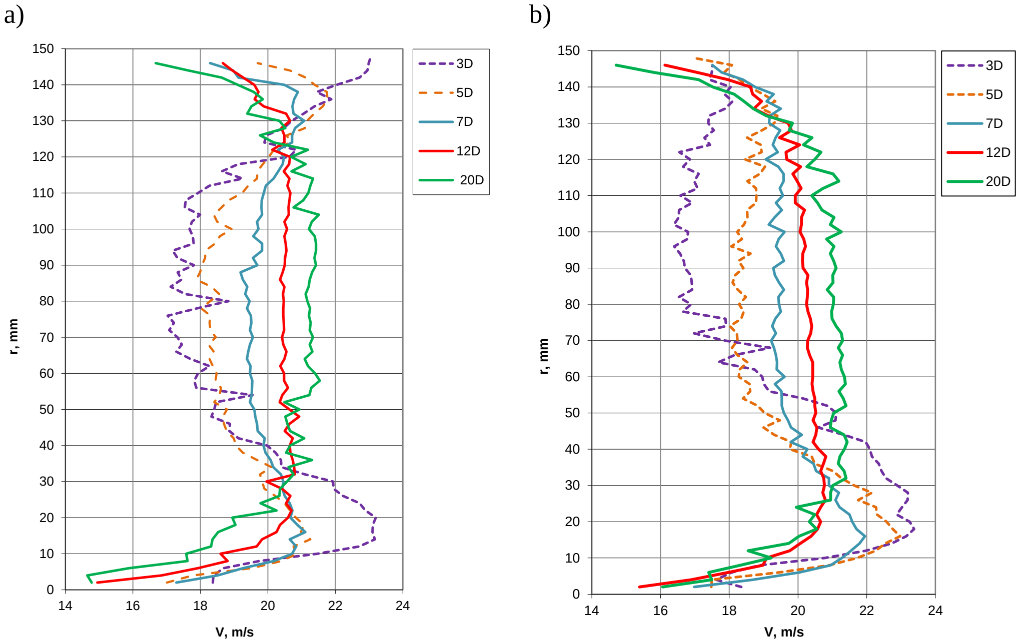


Fig. 7. Velocity profiles behind 90º elbow at average velocity w=18m/s: a) horizontal plane, b) vertical plane.

From the charts a conclusion can be made that the disturbance to the profiles behind the elbow display the characteristics of axial symmetry specific for the horizontal plane (in accordance with data in Fig. 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 in the distance of 12D the velocity profile is symmetrical in both cases and it is completely developed.

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

Additional testing of the inflow effect was undertaken as well for the case when velocity profile was determined for the internal diameter of 152mm. The velocity profiles were determined for the lengths from 2D to 42D for the mean flow velocities of 10m/s, 14m/s, 18m/s, 22m/s and 26m/s. The chart (Fig. 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 is required for the formation of the velocity profile, in which the measurement of the flow by means of any flowmeter will be possible with uncertainty at a preset level. Just as in the case of measurements behind an elbow, the subsequent step involved the testing of selected constructions 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 in the distance of 35D from the inflow was investigated. This involved 4 cases: a pipe without additional elements at the inflow, a confusor with a steel grid of 1×1mm and fabric filters with a small and large density (Fig. 8b).

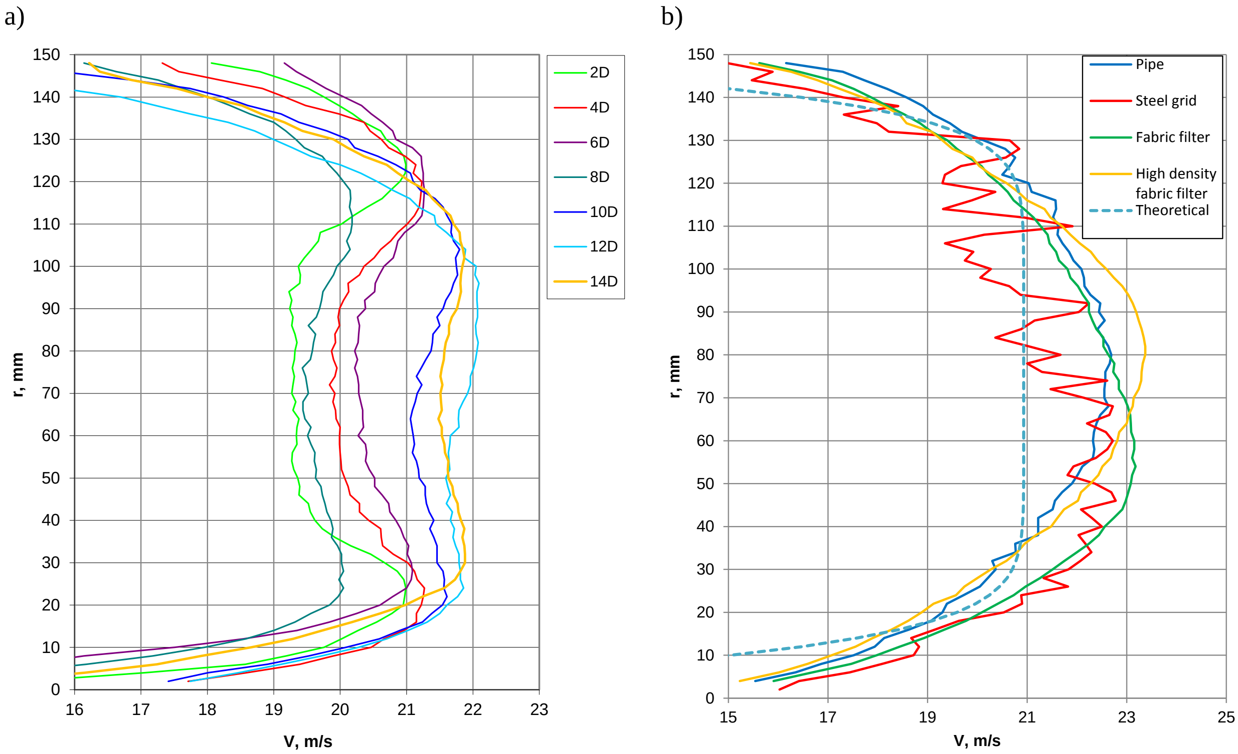


Fig. 8. Inflow effect at average air velocity w=18 m/s (D=152mm): a) velocity profile formation along a pipe, b) influence of different flow resistances at inflow at the distance of 20D.

From the chart one can clearly see that the steel grid plays the role of a turbulizer and the course of the characteristics becomes irregular while the fabric filter tends to smoothen the asymmetrical velocity profile due to the increase of the pressure drop at the inlet. The application of a fabric with a larger density leads to further smoothening of the characteristic, axial symmetry of the course and slight decrease the ratio of the mean velocity to the maximum velocity. Additionally, for the purposes of the comparison, velocity profile is presented for the theoretical data based on the formula [16]:

$$V = V_{max}\left(1 - \frac{r}{R}\right)^{m} \tag{1}$$

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

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=10m/s, 18m/s and 26m/s. Such undertaking was aimed at indication of the advantages of the flow averaging Pitot tubes, one of which consist 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.

The charts presented in Figs. 9 – 13 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 denoted the value equal to 0, the characteristic below the line means a negative velocity (flow reversal) and above 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 26m/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: -8m/s, and the highest velocity (73-40) is 33m/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 200mm and the distance between the adjacent points is equal to 2mm.

Fig. 9 presents local velocity distributions behind the two-profile probe and between the profiles. In the contraction air velocity increases, 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 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 realized every 0.5mm.

a) b)

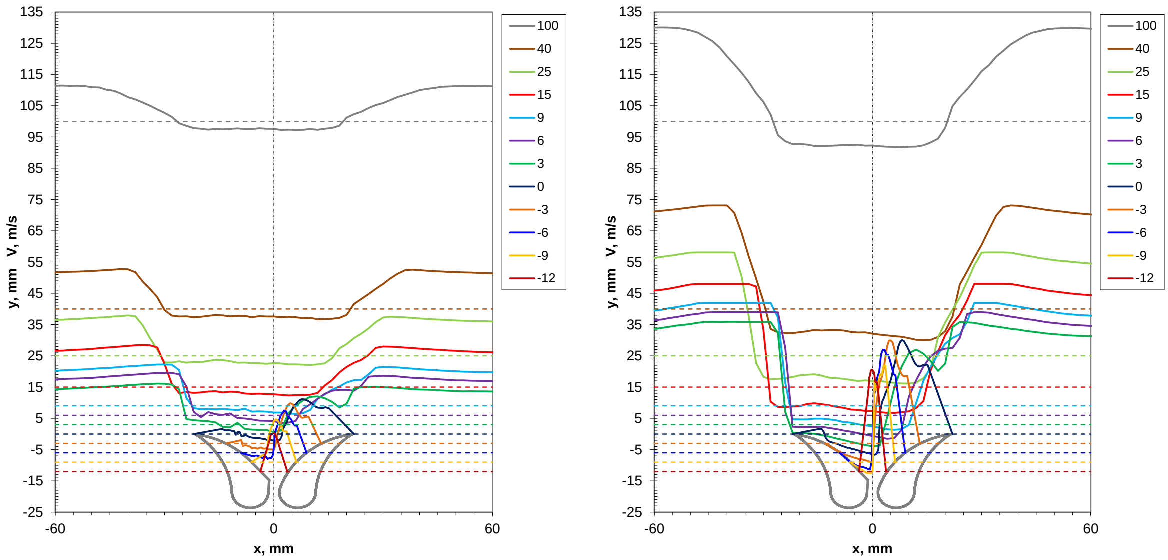


Fig. 9. Two-profile probe: a) mean velocity w=10 m/s, b) mean velocity w=26 m/s.

A probe with a circular diameter (Fig. 10) leads to inconsiderable disturbance of the liquid stream. With an increase of the mean velocity one can note the more intensive recirculation zone in the close vicinity of the streamlined profile.

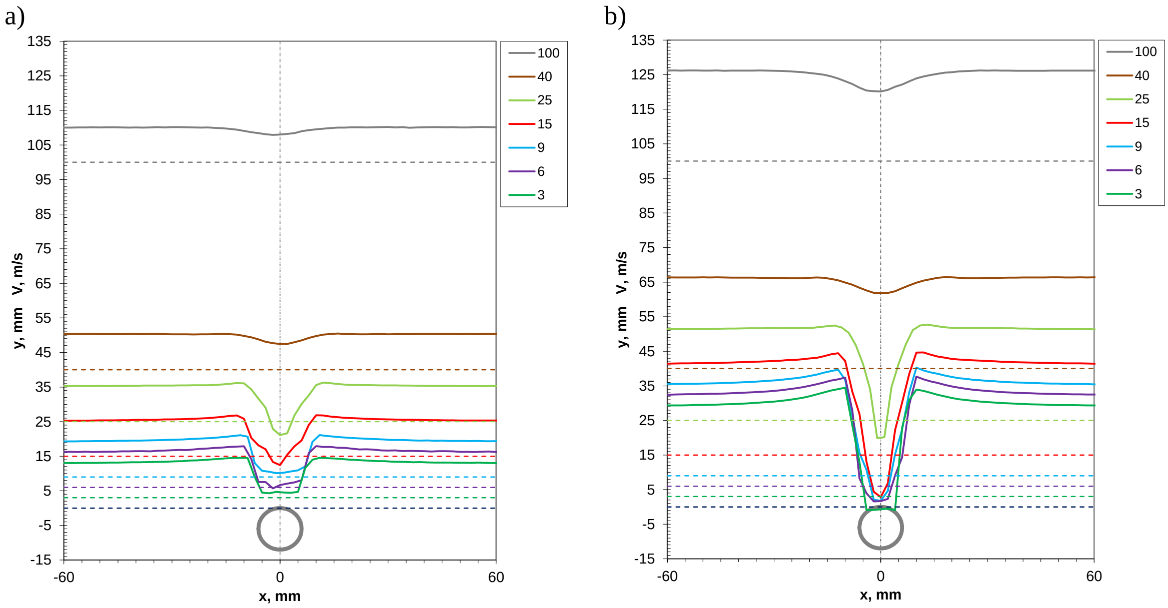


Fig. 10. Cylindrical probe: a) mean velocity w=10 m/s, b) mean velocity w=26 m/s.

The probe with a quadratic cross-section (Fig. 11) leads to considerable pressure drop due to its shape and leaves a wide marked aerodynamic shade effect. The 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=10m/s.

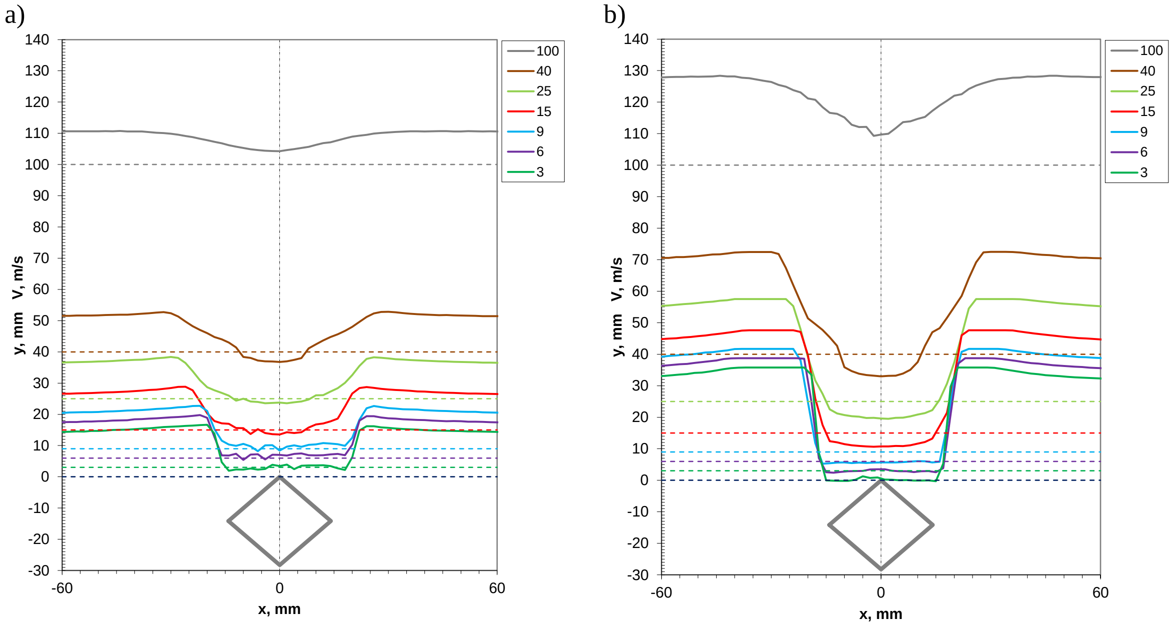


Fig. 11. Square probe: a) mean velocity w=10 m/s, b) mean velocity w=26 m/s.

Fig. 12 illustrates 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 the ones registered behind the cylindrical probe (Fig. 10).

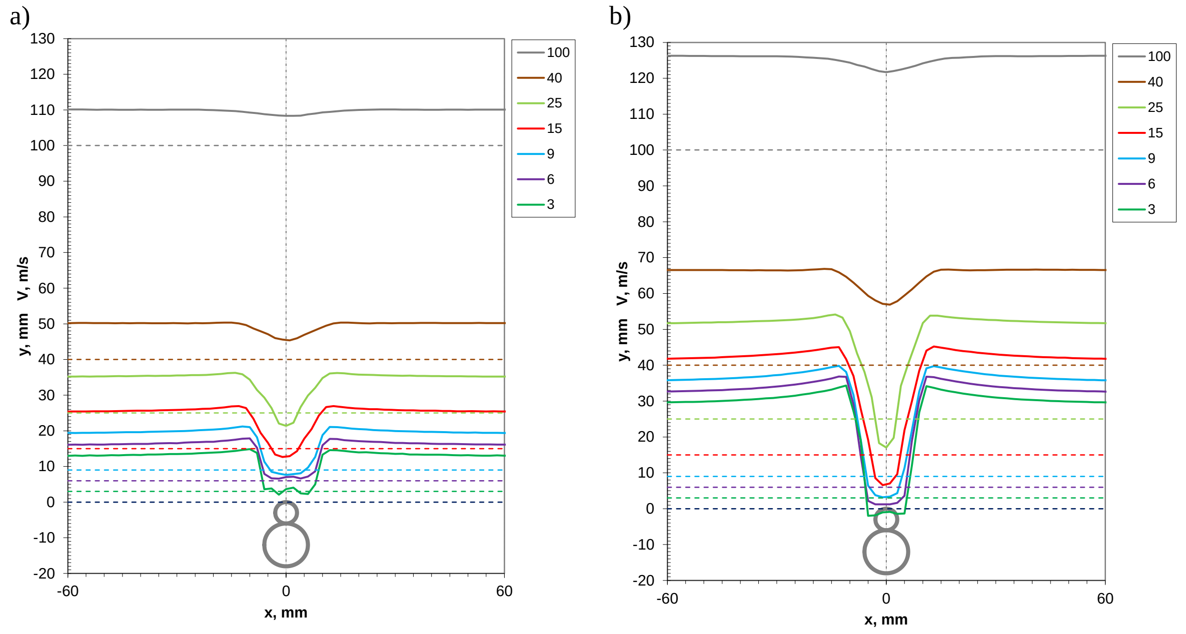


Fig. 12. Double-cylindrical probe: a) mean velocity w=10 m/s, b) mean velocity w=26 m/s.

The probe with streamlined cross-section (Fig. 13) leads to the smallest disturbance of the velocity profiles in comparison to the previous cross-sections due to the side walls situation under the angle of 14º in relation to the incoming stream. From the charts it stems that the recirculation of the streams occur in the narrow area behind the probe – between 3 and 15mm.

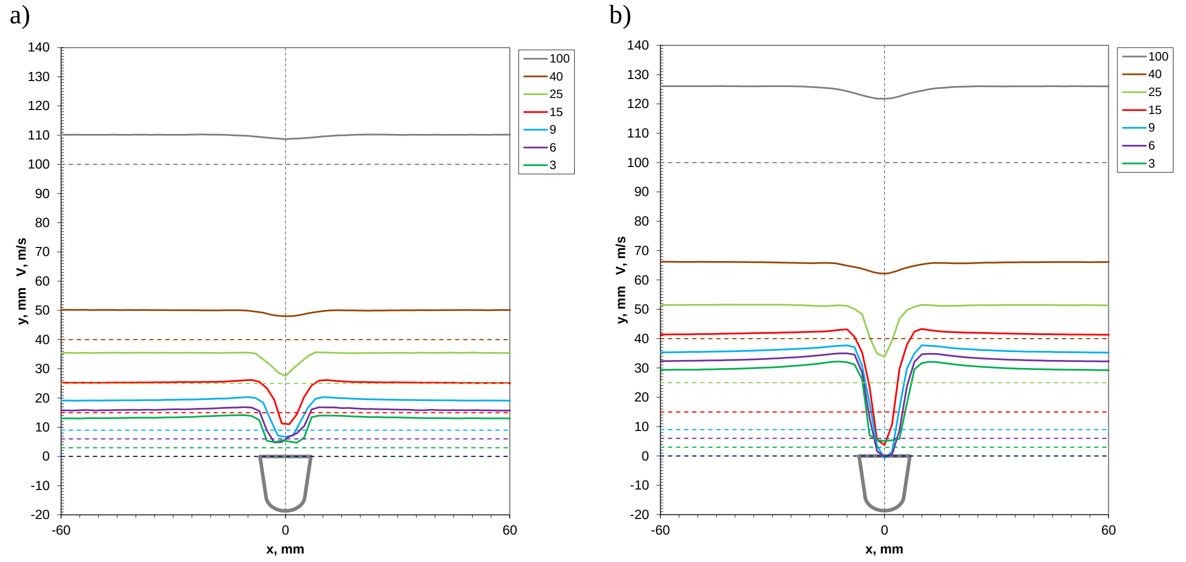


Fig. 13. Streamlined probe: a) mean velocity w=10 m/s, b) mean velocity w=26 m/s.

The resulting characteristics present results averaged in time. The phenomena occurring in the vicinity of the streamlined profiles are variable in time and a have periodical nature. Due to the considerably large velocities, it is difficult to register the behavior of the liquid streams in 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 ANSYS FLUENT program [17, 18] during the inflow of air stream with a plane velocity profile, if it corresponded with the conditions of the research conducted in wind tunnel. For all cases considerable qualitative conformity was obtained. It was remarked that the smallest conformity was gained for the case of two-profiled probe. The testing was performed on a structural mesh by application of the available turbulence models and the best results were gained for the k-ω model. Fig. 12 presents exemplary results of numerical simulation of the two-profile probe. This probe offers a local resistance to air stream dashing them away in the rear part; thus, causing alternate vortices on one and the other side in the aerodynamic shade of the profiles.

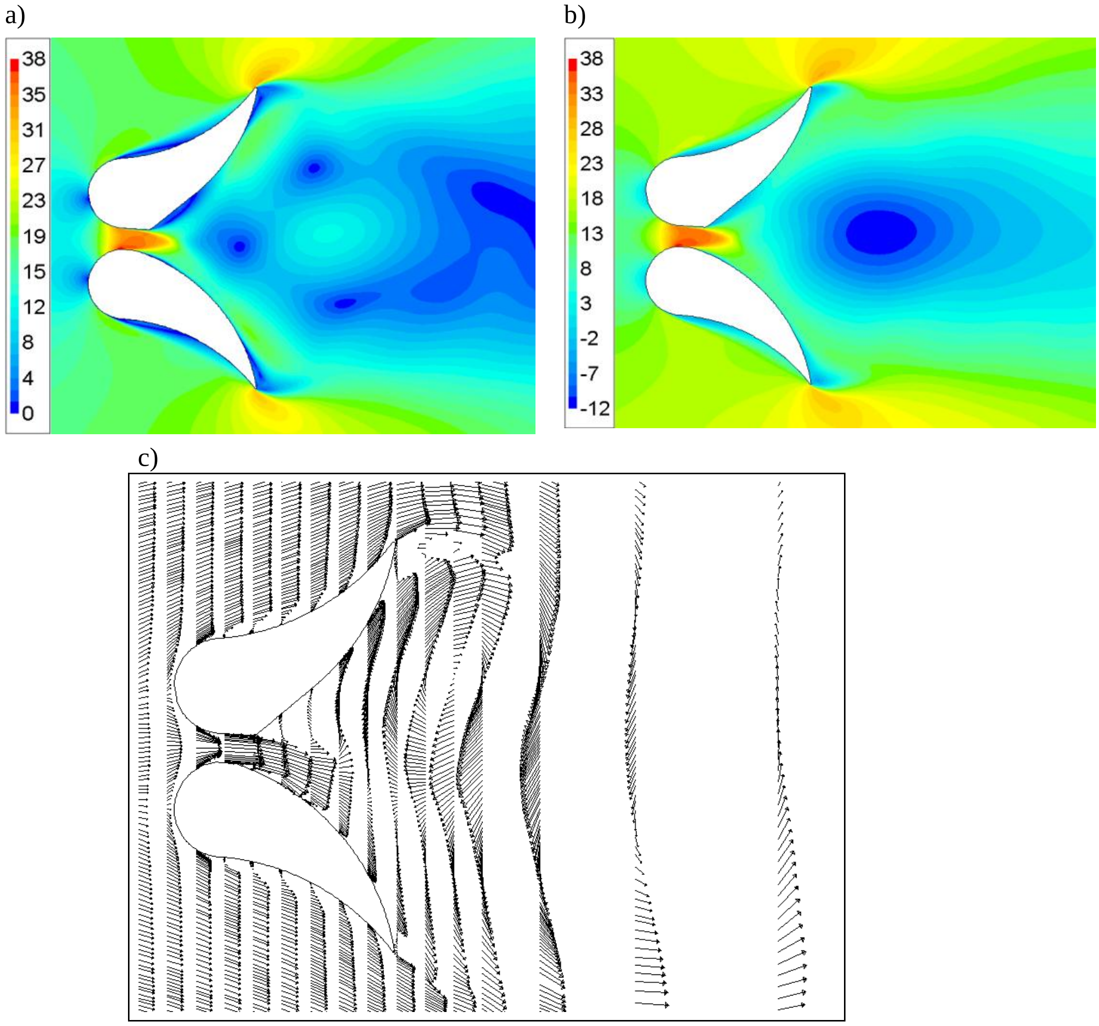


Fig. 14. Exemplary numerical simulation results for two-profile probe for inflow mean velocity w=18m/s: a) contours of mean velocity magnitude, b) contours of mean x velocity, c) velocity vectors.

The streamlined flow around the cylindrical probe generates von Kármán's vortex street, which after statistical averaging takes the form presented in Fig. 15. The statistical distribution maps indicate the qualitative and quantitative conformity of the resulting flow maps.

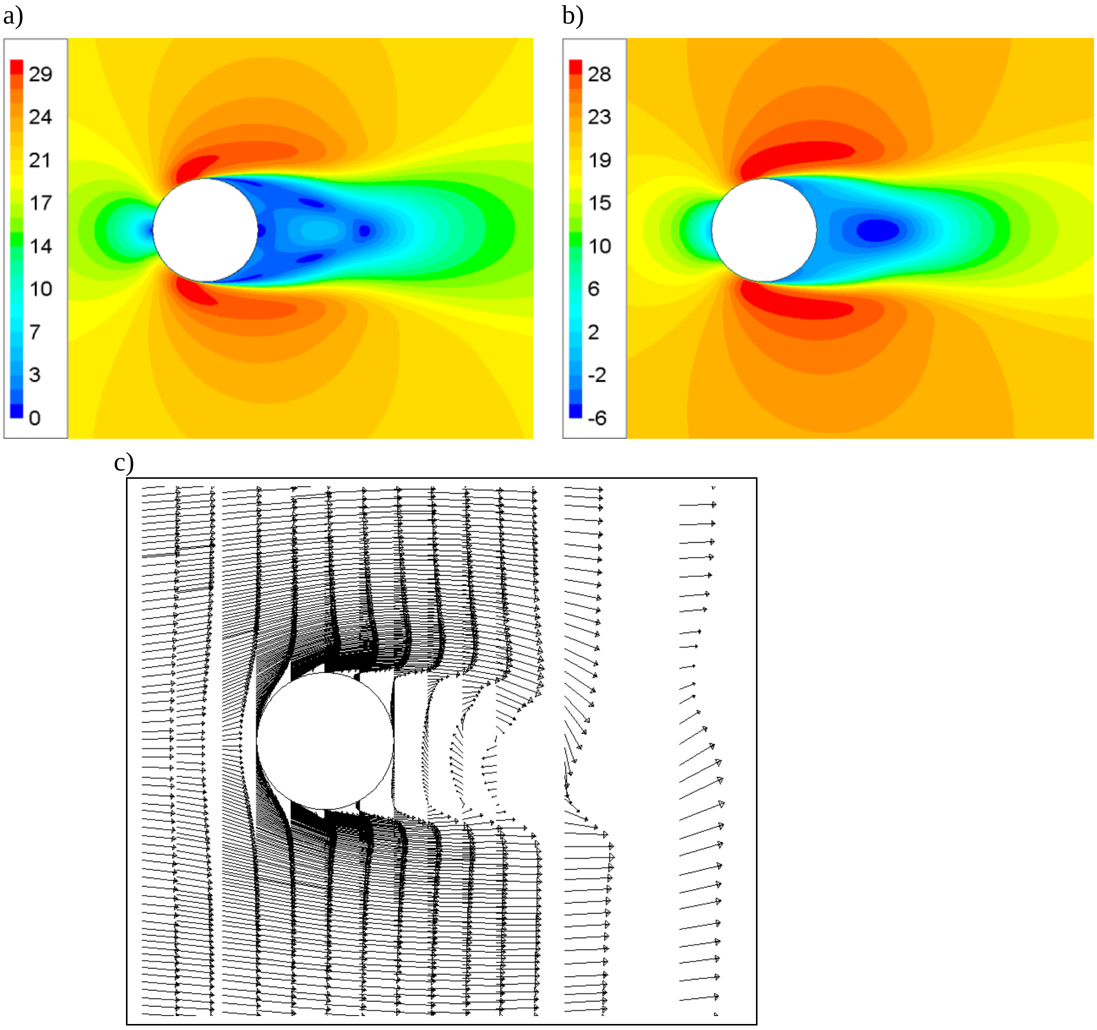


Fig. 15. Exemplary numerical simulation results for cylindrical probe cross-section for inflow mean velocity w=18m/s: a) contours of mean velocity magnitude, b) contours of mean x velocity, c) velocity vectors.

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 previously presented results of experiments. Due to the variety of characteristics in the chart, the graphical comparison was not possible on a single chart. The velocity profiles are similar to the ones gained from the experiments.

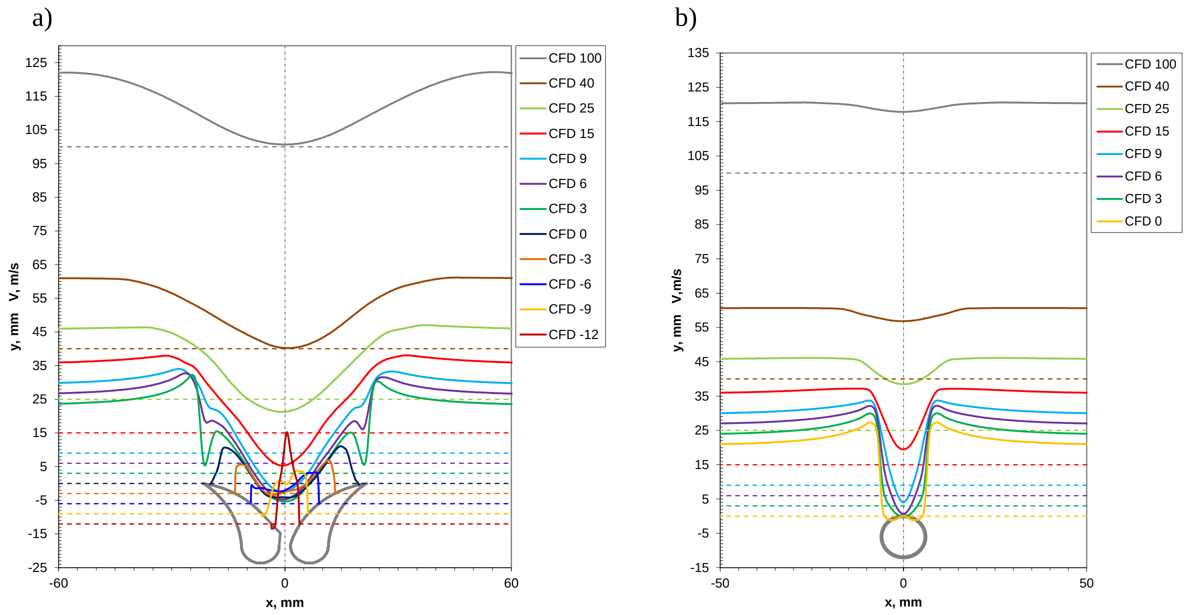


Fig. 16. CFD-based x-velocity component distribution at mean velocity w=20m/s behind: a) two-profile probe, b) circular cross-section probe.

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

5. CONCLUSIONS

The presented fully automatic measurement stand offers the possibility of registration of velocity profiles on the basis of a large number of measurement points set at a distance of 0.1 mm from one another. The linear model is capable of co-operation with the Pitot tube, two-direction probe or any other device which undertakes the measurement of the local velocity (laser flowmeter, thermal one).

The research conducted in pipelines offers 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 one required by the manufacturer without additional uncertainty of measurement after certain corrections are accounted for [10].

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

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 the experiments. The conformity between the experiments and numerical simulations is satisfactory; however, there is a need to analyze all 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 the spots of disturbed flow. The comparison of such data with the results gained from numerical simulations will make it possible to precisely determine the applicability of selected calculation methods applying 3-D modeling.

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