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ANALYSIS OF APPLICABILITY OF FLOW AVERAGING PITOT TUBES IN THE AREAS OF FLOW DISTURBANCE

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Abstract

The issues connected with the complex design of various facilities, including up-to-date boiler equipment as well as the ways of organizing the space around them, are the reasons why there is often a lack of room for mounting a flowmeter in accordance with the recommendations of manufacturers. In most cases the problem is associated with ensuring sufficient lengths of straight pipe leading into and out of a flowmeter. When this condition cannot be fulfilled, the uncertainty of measurement increases above the value guaranteed by the manufacturer of the flowmeter. This sort of operation problem has encouraged the authors of this paper to undertake research aimed at the analysis of applicability of averaging Pitot tubes in the areas of flow disturbance.

Keywords: averaging Pitot tubes, flowmeter, measurement uncertainty.

1. Introduction

The measurements of mass and volume flow rates are some of the most common processes in industry. Over many years averaging Pitot tubes and – in particular – orifice plates were listed in the most common groups of flowmeters. The measurement based on application of an orifice has undergone normalization due to its common use [10]. When flow takes place in channels with a large diameter (D > 800 mm), and, in particular, in the conditions when the medium has a high temperature of several hundred °C, it is difficult to find a better solution than a common Pitot tube. Therefore, in such circumstances averaging Pitot tubes offer an alternative solution for a classical venture tube. Flowmeters with flow averaging Pitot tubes are becoming more and more common as a consequence of smaller pressure drops caused by their presence in the installation, as well as considerably lower installation and maintenance costs compared with those of full-bore flowmeters [22, 24, 25].

An additional measurement uncertainty is associated with the lack of sufficiently long sections of axial pipeline before a flowmeter [1, 2, 11, 12, 20]. Its value and sign is relative to the distance between the flowmeter and the obstacle. For flow averaging Pitot tubes, the measurement uncertainty is relative to the plane of the flowmeter installation as well as its design, including its profile and location of tapping points [2]. The information regarding the level of this uncertainty in a given location can have a decisive role in determining whether it is applicable for instance in regulating air flow into a combustion process or in controlling turbo-compressors. The research was performed for a variety of profiles of flow averaging tubes and elements used for flow disturbance. This paper reports the results obtained from analysis of applications of tubes with a circular and streamlined cross-section installed in various locations behind a segmented elbow and a slide.

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2. Flowmeters and test stand applied in research

Averaging Pitot tubes, as well as various types of micro-orifice plates, are used for reliable measurements of liquid velocity and determination of velocity profiles. The types of flowmeters used in the field and designs of pressure tapping bores tend to ensure maintaining reasonably constant values of the coefficient K over a range of flow conditions. The value of K is most often within the range 0.6 ÷ 0.8.

The velocity measured during the measurement with an averaging Pitot tube is determined from the relation:

$$v = K\sqrt{\frac{2\Delta p}{\rho}}, \tag{1}$$

where: K – the flow coefficient; Δp – the differential pressure; ρ – the liquid density.

The volumetric flow rate during the measurement with an averaging Pitot tube is calculated from the relation:

$$q_v = KA\sqrt{\frac{2\Delta p}{\rho}}, \tag{2}$$

where: q_v – the volumetric flow rate; A – the pipeline cross-section area.

The values of K are generally determined on the basis of probe calibration. Their values are affected by the cross-section of the probe and the location of the sensing ports. For low values of the flow rates the parameter K is also relative to the Reynolds number and rises along with an increase of it [22, 24]. In industrial practice we can find probes with various cross-sections, which results in the form of variations of the flow coefficient [5–9, 15, 26]. Research is under way to find a design of the probe with the most beneficial metrological parameters [14, 15]. On the other hand, such probes need to withstand various conditions, such as vibrations and stress, as a result of various flow velocities. For high velocities of the fluid flow, it is necessary to take into account the effect of fluid compressibility on the value of K. This effect is accounted for in the form of a multiplier. Its value is relative to the Mach number which is applied to account for specific flow conditions [3]. Testing such flowmeters also employs mathematical modeling, numerical methods and digital simulation [16, 18, 19]. This methodology was used *e.g.* in testing distribution of the pressure over the surfaces of probes [2, 14], the movement of fluid inside dynamic pressure averaging chambers [3], or in looking for an effect of non-Newtonian characteristics of fluid on the velocity measured by a Pitot tube [4]. The results of numerical calculations often include a considerable degree of error, which value is relative to the number of elements in a mesh, the adopted turbulence model and the type of differential diagrams. The study in [23] involved a formulation of the criteria which can be helpful in assessment of the results of numerical calculations and, in particular, velocity profiles in the channels derived with digital computations.

The presented research concerns two designs of averaging Pitot probes installed at two different distances from the flow obstacle. Fig. 1 presents the design of flowmeters used in this research. The examined designs of flow averaging tubes include three pressure tapping bores located in the direction of the incoming flow, which were arranged in accordance with the principle of dividing a circle into a set of concentric equal-surface rings [25]. By analogy, six points were used for tapping under-pressure. Fig. 2 presents the cross-sections of the analyzed averaging Pitot tubes.

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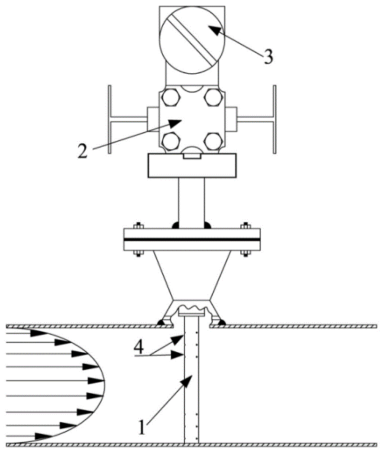


Fig. 1. An averaging Pitot tube: 1) sensor; 2) block valve; 3) differential pressure transducer; 4) pressure tapping bores.

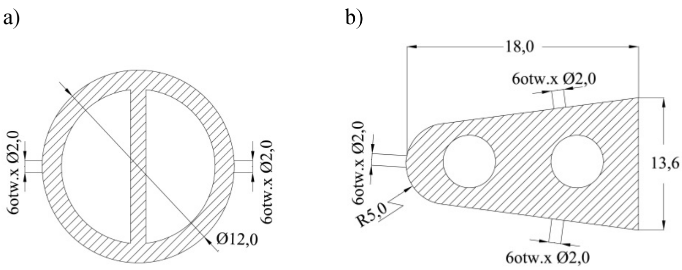


Fig. 2. An averaging Pitot tube: a) the probe with a circular profile (Accubar); b) the probe with a streamlined profile (Introbar).

The experimental set-up includes a wind tunnel and a system of pipelines with the diameters of DN 110 to DN 400 with – used for reference – two Sponsler turbine precision flowmeters with the measurement uncertainty of less than 0.5% [13, 21]. The set-up additionally contains a top-of-the-range system for data registration, visualization and storage based on the LabView environment [17]. The set-up is used for testing flowmeters including assessment of the effect of disturbance of the velocity profile on the results. Fig. 3a presents a photo of the set-up, and Fig. 3b shows a simplified diagram of the set-up for the scope of performed testing. The use of the top-of-the-range measurement equipment enabled determination of the total uncertainty of the flow coefficient *K* with regard to the measured pressures and air temperatures given for a constant uncertainty of the flow rate and a constant pressure drop measurement uncertainty to be kept within the range of ± 0.71%.

The testing involved the effect of velocity disturbance resulting from installation of a 3 x 30° segmented elbow and a throttle. The elbows used in the research were purchased from a single manufacturer. The details of their dimensions are shown in Fig. 4. The type of valve used in the research and its dimensions are summarized in Fig. 5.

Fig. 3a. The experimental set-up.

The detailed layout of the setup is presented in Fig. 3b.

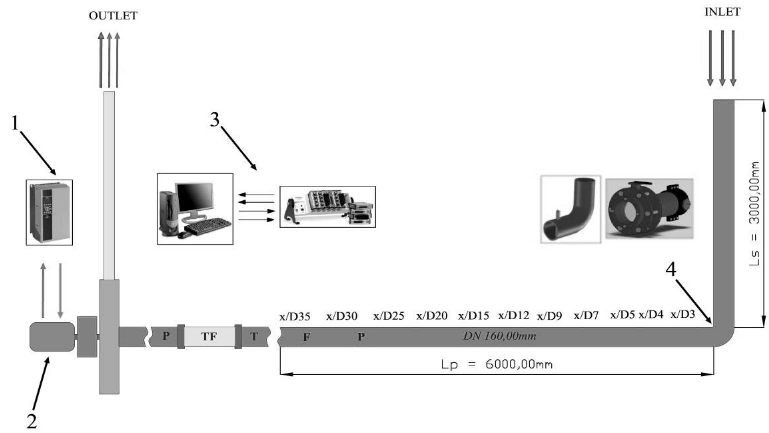
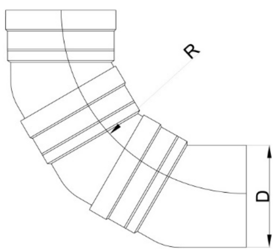


Fig. 3b. The layout of the experimental set-up: 1) frequency inverter; 2) electric engine; 3) data acquisition system; 4) flow disturbing element; P – measurement of absolute pressure; T – measurement of temperature; TF – turbine flowmeter; Lp – test section; Ls – flow stabilization section.



R, mm	D, mm	R/D
294	152	1,93

Fig. 4. Dimensions of the elbow.

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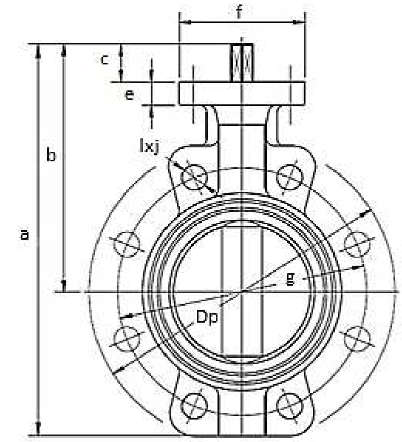

DN	F	C	e	b	a	D_p	G	I	J	Weight
Mm									no.	kg
160	90	30	15	223	357	285	240	23	8	12

Fig. 5. Dimensions of the valve.

3. Methodology and results

In order to determine the deformation of the velocity field in the points of pressure tapping given by the examined flowmeters, the axial velocity profiles were identified. In the performed testing the Pitot tubes were installed with a system for traversing the measurement area in the point marked in Fig. 3 in several distances x/D from an element used for the flow disturbance in two planes relative to the obstacle (VERTICAL, HORIZONTAL). The testing procedure involved installation of the Pitot tube in the measurement section starting from the furthest distance from the flow obstacle of x/D35 in two planes (VERTICAL, HORIZONTAL) and finishing with the smallest distance of x/D3. Fig. 6 illustrates the way of using the system for traversing the measurement space and the Pitot tube.

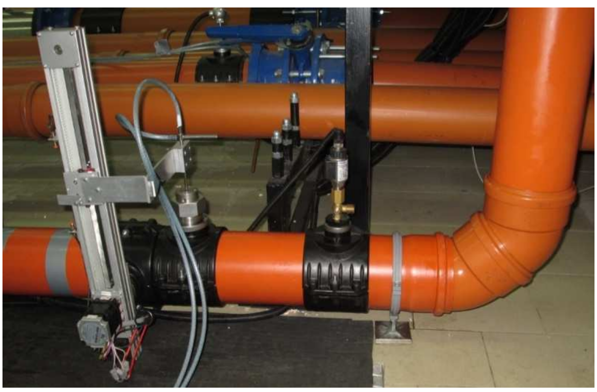

Fig. 6. The way of installing the system for traversing the measurement space and the Pitot tube.

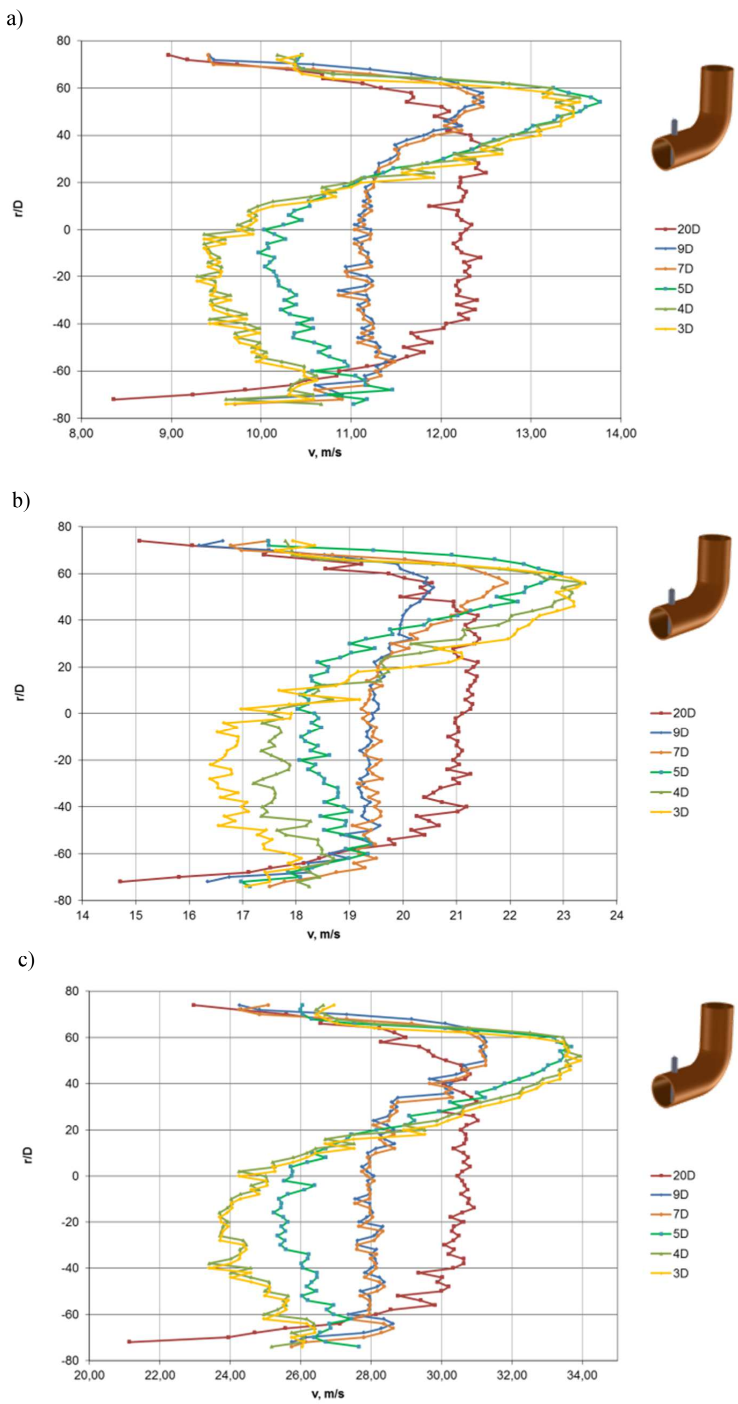

Fig. 7. The velocity profiles in the elbow plane (for the mean velocity: a) 10 m/s; b) 18 m/s; c) 26 m/s).

After completion of the research in all configurations, the measurement section of the pipeline Lp was replaced with a new one. The results regarding velocity profiles contain 72 measurement points. On the charts, each of the points which determines the velocity is obtained

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from averaging the registration taken over several seconds. The absence of smooth lines on the charts results from the occurrence of flow disturbance, operation of the system used for blower capacity regulation, and the scale adopted in the charts. Figs. 7 and 8 present the velocity profiles derived in the distances and planes behind the 3 x 30° segmented elbow. These profiles were obtained for the DN 160 pipeline for three different mean flow values, equal to 10 m/s (Re = 9,71 x 10^4), 18m/s (Re = 1,75 x 10^5), 26m/s (Re = 2,52 x 10^5), respectively.

For the vertical location, as presented in Fig, 7, the velocity indicates a considerably asymmetrical distribution of the local flow velocities. Such a large deformation of the velocity profile can have a considerable effect on the results of measurements undertaken with the use of various types of averaging Pitot tubes. The velocity profiles shown in Fig. 8 result from the testing performed for the horizontal installation of the probe. The velocity profile even at the relative distance of 9 times the diameter of the elbow is close to the profile which was treated as fully developed. For the system with the obstacle in the form of a segmented elbow, the distance from the obstacle equal to 20 times the diameter of the pipeline is considered to become fully developed.

Testing the analyzed averaging Pitot tubes was performed in similar locations (pipeline cross-sections) as those for the velocity profiles. Installation of the probe in the measurement section started from the furthest distance from the obstacle (x/D35) and ended at the smallest distance of x/D3. Such a procedure of testing was adopted in order to minimize the effect of the installation holes on the results of measurement. The openings in the pipeline after the completed measurement series were sealed and the same course of action was followed for measuring the velocity profiles. The measurements within the range of 10 ÷ 30m/s were taken at each installation place of the probe. For the range of mean velocities derived in this way, 93 flow coefficient K values were obtained. Fig. 9 presents the flow coefficient value for the Introbar probe, while Fig. 10 – the results of measurements for the Accubar probe within a few distances from the obstacle in the form of a 3 x 30° segmented elbow. The summary of data presented in Figs. 9 and 10 contain a comparison of the effect of the obstacle on the flow coefficient of analyzed probes. Analysis of the charts enables the designer to select a flowmeter which is least sensitive to flow disturbance in a given location. The vertical orientation of analysed probes is most effective from the point of view of metrological measurements. This is particularly noticeable for a streamlined probe, when the deviation from the K/K_{20} value equal to one does not exceed ± 0.03. Such a range of deviation values over the entire length of the section where the probes were installed also means that the streamlined probe is less sensitive to symmetrical deformation of the velocity profile than the probe with a circular profile. A possible explanation is associated with different positioning of pressure tapping bores on the under-pressure side. This could also be affected by three-dimensional characteristics of the liquid motion and the impact of complex velocity and pressure fields on the probe. This issue needs to be studied further. The results of research indicate a slight deviation in the value of K coefficient in the probe with a circular profile when it is installed in the distance of 3 ÷ 5D from the pipe elbow (for the horizontal orientation of the probe). This should be seen as a point against the use of the probe with a circular profile in these conditions. The value of K was not determined in the distance from the elbow smaller than 3D, whereas the variations in the value of K in the distance of around 4D from the elbow tend to be considerable. In addition, it is possible to note the effect of mean velocity on the value of K coefficient. For this probe, stabilization of the flow coefficient value can be obtained when the distance of its installation from the elbow exceeds 12 times the dimension of the pipeline.

As a result of determining the velocity, it was possible to analyze local velocities for the locations which correspond to the distribution of sensing ports in the analyzed designs of averaging probes. Figs. 11a and 11b contain a summary of the velocities in the specific sensing ports of the examined flowmeters installed in the plane of the elbow and in the plane which is perpendicular to it for the mean flow velocity of 18m/s.

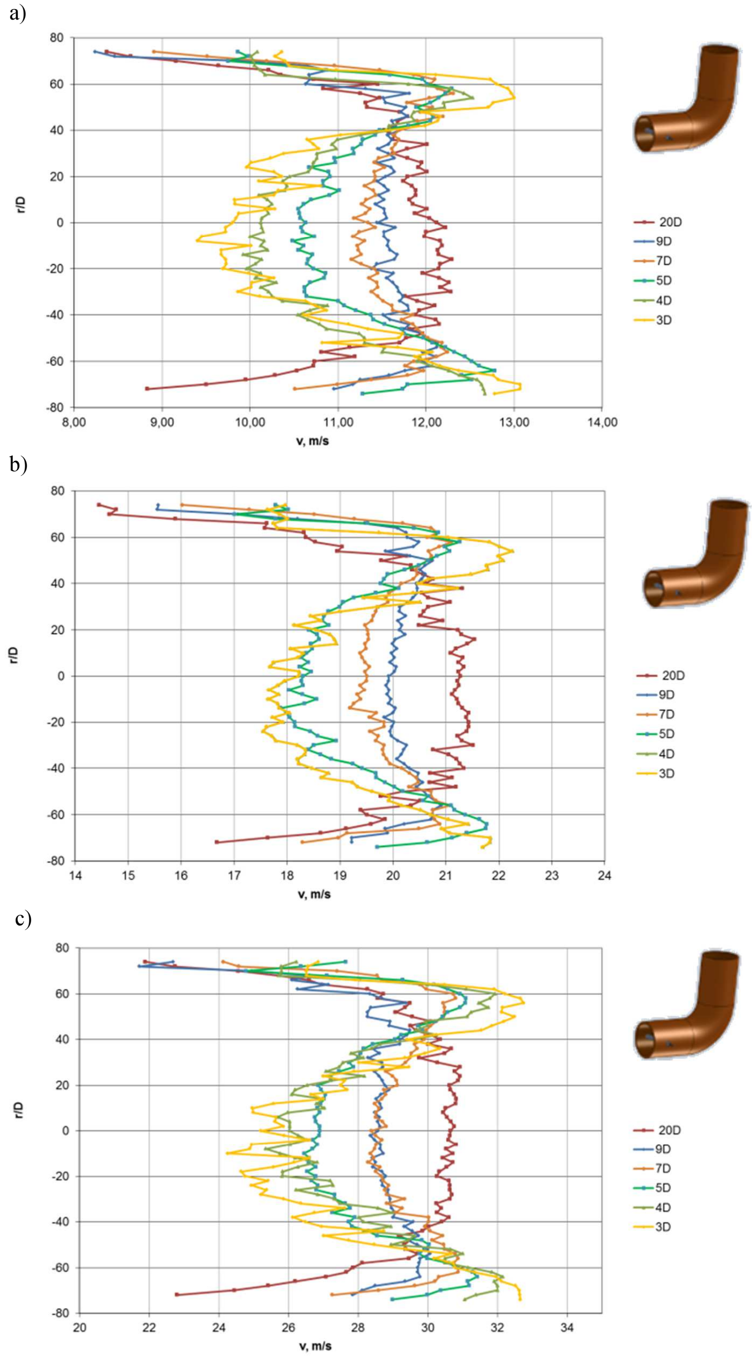

Fig. 8. The velocity profiles in the plane perpendicular to the elbow (for the mean velocity: a) 10m/s; b) 18m/s; c) 26m/s).

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a)

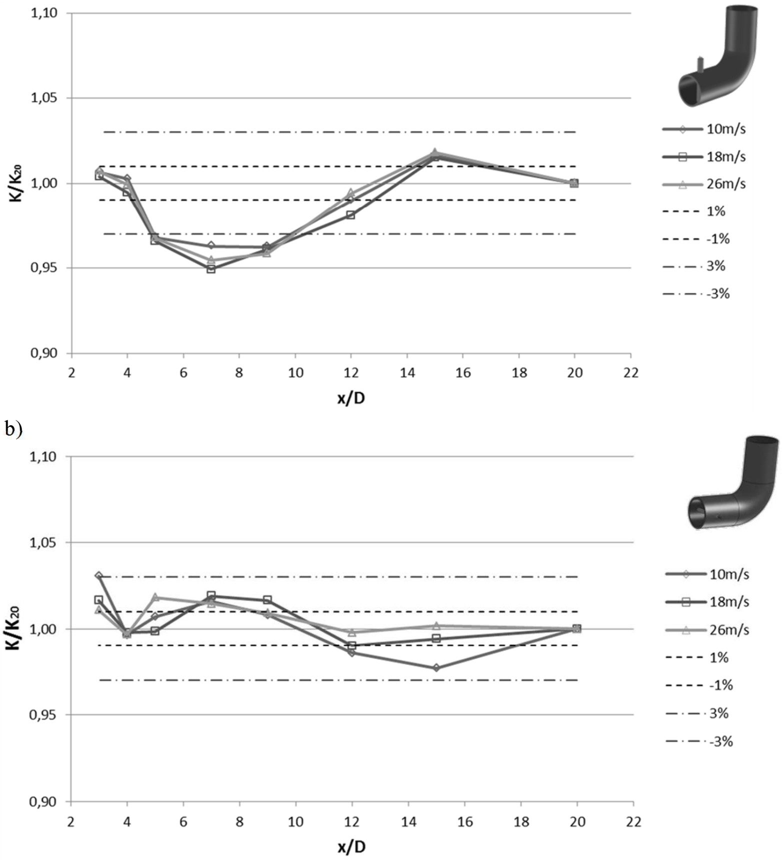

Fig. 9. The flow coefficients K/K_{20} of Introbar flowmeter as a function of the distance from the obstacle: a) the vertical orientation of the probe; b) the horizontal orientation of the probe.

For the vertical probe orientation, the local velocities in the specific pairs of sensing ports assume similar values along with the increased distance from the obstacle, which indicates that the velocity profile is stabilized. However, in Fig. 11b these values in the extreme sensing ports (r_3 and $-r_3$) are not convergent. This could be caused by the measurement technique applied in this test, since small variations in positioning of the probe in a small distance from the pipeline wall, where large velocity gradients are present, could lead to considerable divergences in registration of the measurement results.

Figures 12a to 12d illustrate the results of measurements for the two analyzed probes installed in several distances from the obstacle in the form of a throttle for its two opening stages. The results were performed for two positions of the probe with respect to the throttle, *i.e.* the vertical (parallel to the axis of the working element) and horizontal ones. The effect of flow disturbance on the results indicated by the flowmeter were analyzed by setting the flow coefficient K for a given location of the flowmeter to the value K_{35}, where it was assumed that the velocity profile had completely developed.

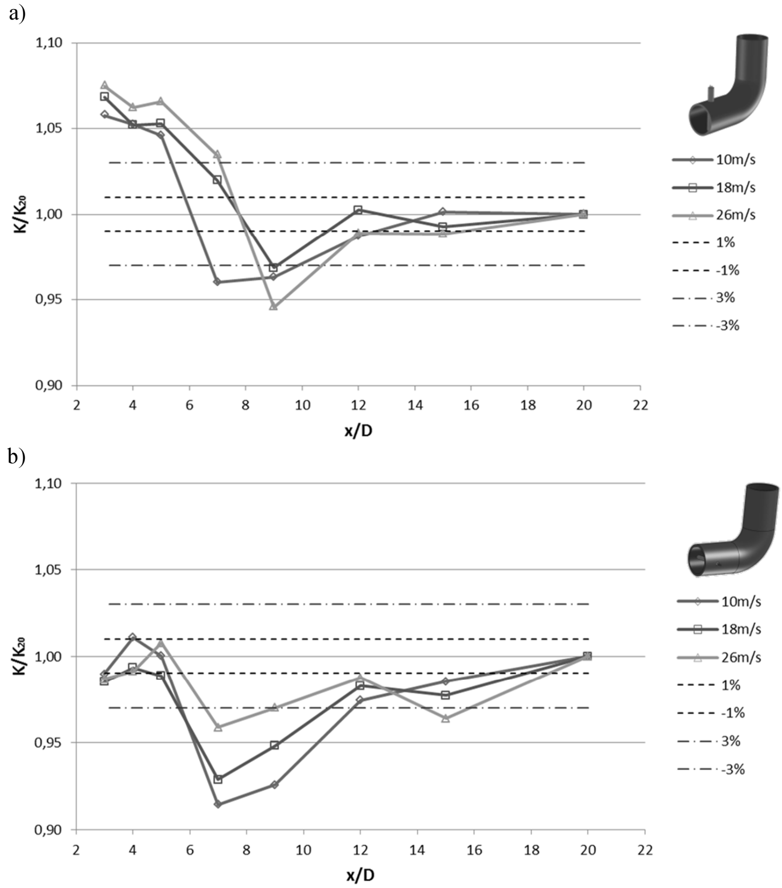

Fig. 10. The flow coefficients K/K_{20} of Accubar flowmeter as a function of the distance from the obstacle: a) the vertical orientation of the probe; b) the horizontal orientation of the probe.

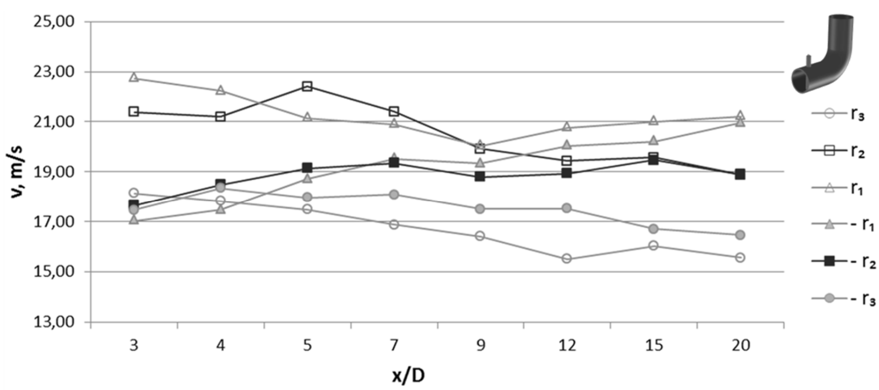

Fig. 11a. The velocities in the particular piezo-metric holes of the examined flowmeters in the plane of the elbow for the mean flow velocity of 18 m/s, the vertical probe orientation.

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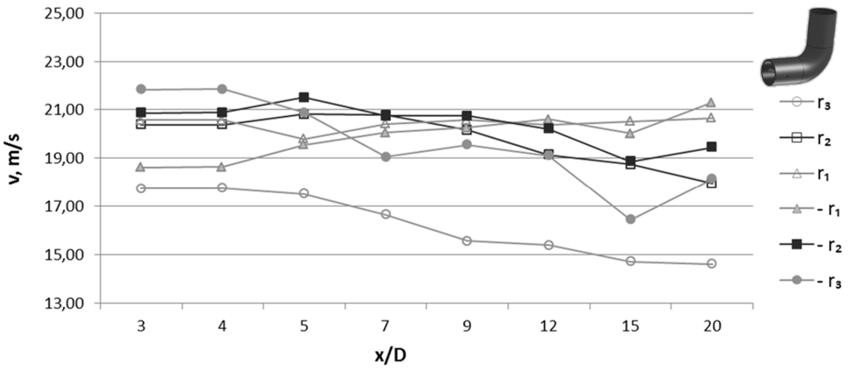

Fig. 11b. The velocities in the particular piezo-metric holes of the examined flowmeters in the plane perpendicular to the elbow for the mean flow velocity of 18m/s, the horizontal probe orientation.

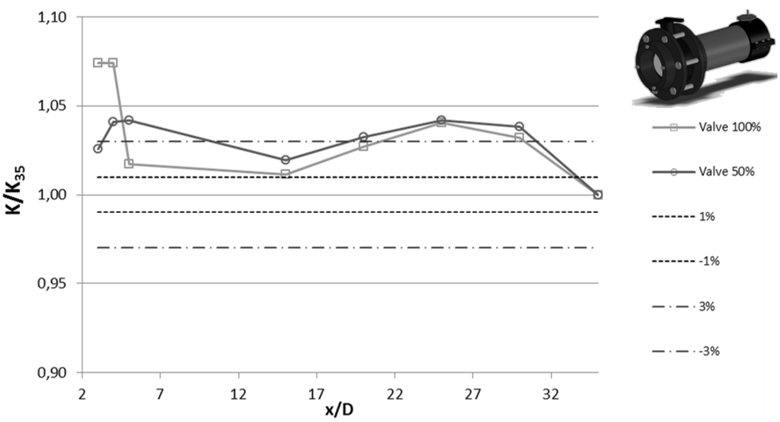

Fig. 12a. The flow coefficients K/K_{35} of Introbar flowmeter as a function of the distance from the obstacle for the mean flow velocity of 18m/s, the vertical probe orientation.

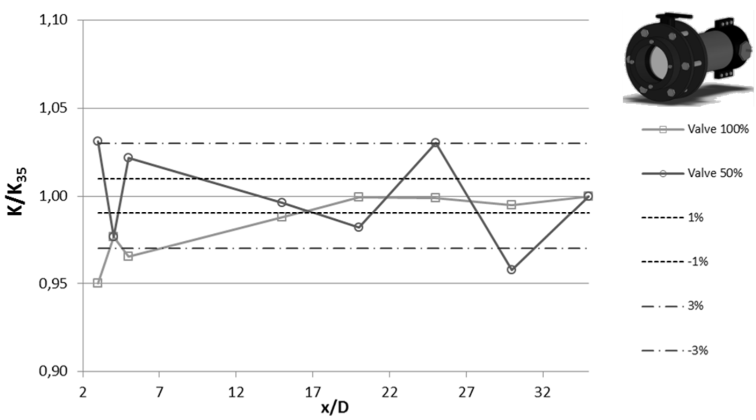

Fig. 12b. The flow coefficients K/K_{35} of Introbar flowmeter as a function of the distance from the obstacle for the mean flow velocity of 18m/s, the horizontal probe orientation.

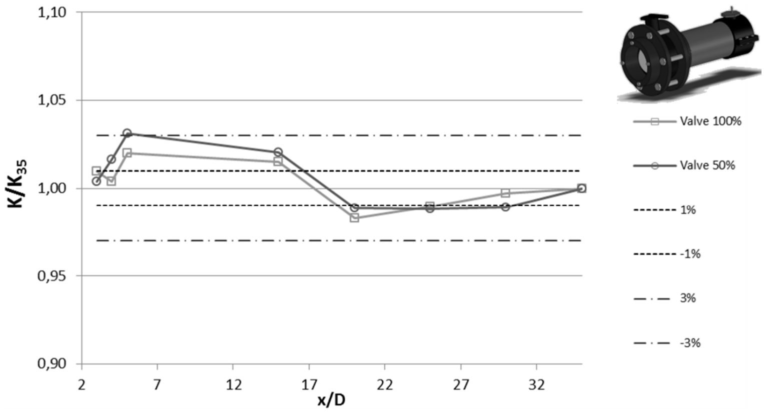

Fig. 12c. The flow coefficients K/K_{35} of Accubar flowmeter as a function of the distance from the obstacle for the mean flow velocity of 18m/s, the vertical probe orientation.

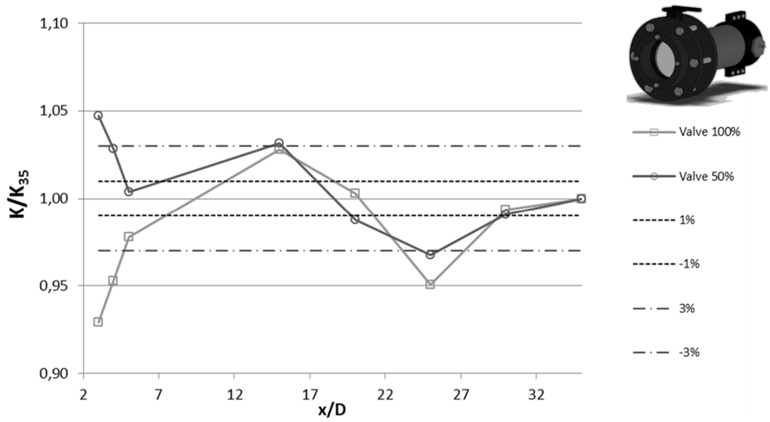

Fig. 12d. The flow coefficients K/K_{35} of Accubar flowmeter as a function of the distance from the obstacle for the mean flow velocity of 18 m/s, the horizontal probe orientation.

For the horizontal orientation of the probes with respect to the throttle, where the disturbance of the velocity profile is symmetrical to all analyzed probes, the deviation of K/K_{35} is larger. The vertical orientation of the probe is more advantageous from the metrological perspective. The results of this research indicate a considerable deviation of K coefficient for for the horizontal orientation of the Accubar probe installed at the distance of 25D from the throttle in the fully open position. This indicates that the Accubar probe cannot be applied in these conditions. Concurrently, for the vertical and horizontal orientation at the distance of 3 ÷ 5D, the Introbar probe indicates the deviation of the value K/K_{35} exceeding in extreme case ± 6.0%, which suggests that it should not be applied in this orientation. However, for both analyzed probes starting from the distance of 15D for the vertical orientation, one can note that there is no effect of the opening stage on the value of K coefficient.

4. Conclusions

This paper reports the results of research on the effect of typical flow obstacles on the flow coefficient of two designs of flow averaging Pitot tubes. The research involved testing the effect of disturbance caused by installation of a 3 x 30° segmented elbow and a throttle with two

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opening stages and their impact on the value of flow coefficient measured by the tested flowmeters. Analysis of the research results indicated that it is possible to successfully apply averaging Pitot tubes in a smaller distance than the one recommended by the manufacturers. For a 3x30° segmented bend, the velocity profile in the close vicinity of the flow obstacle demonstrates a considerable degree of deformation. This deformation is asymmetric and causes a deviation in the flow coefficient from the value K_{20} for the undisturbed flow. The largest range of these variations occurs for installation of probes in the plane of the bend (*i.e.* the vertical orientation) for the Annubar (± 6%) and Introbar probes (± 4,5%). Behind the throttle in the completely open position the velocity profiles indicate asymmetric distribution of local velocities in the vicinity of the pipeline wall for all analyzed values of the mean velocity. The velocity profile even in a relative distance of 10 times the diameter of the pipeline is close to the profile which was identified to be fully developed. The type of disturbance results in deviations of the flow coefficient from the value K_{35} for the undisturbed flow. The highest range of these variations for the distance of probe installation related to the flow obstacle is observed, respectively, for the Annubar probe (± 6.6% for the distance of 3x/D and the horizontal orientation of the probe) and the Introbar probe (± 6.4% for the distance of 3x/D and the vertical orientation of the probe). Behind the throttle open to 50% of its throttling range, despite a considerable disturbance of the stream, the velocity profile is stabilized in a short time. The velocity profile in the relative distance behind the obstacle equal to 10 times its diameter is in this case close to that identified as a fully developed one. For the completely open throttle, the largest range of the variability in the flow coefficient takes place for the Annubar probe (±5,0% for the distance of x/D3 and the vertical orientation of the probe), whereas the smallest range of these variations is observed for the Introbar probe (± 2,4 for the distance of x/D3 and the vertical orientation of the probe). The total uncertainty level of ± 3.0% to ± 4.0% makes the analyzed flowmeters applicable in a variety of regulation systems in technology processes, such as controlling the combustion process. The research additionally provided grounds for proposing metrological recommendations and the results indicated that not only the distance from the obstacle but also the plane in which the flowmeter is oriented has an influence on the uncertainty of measurement by the examined flowmeters.

References

[1] Baker, R.C. (2000). *Flow Measurement Handbook.* University of Cambridge.

[2] Chmielniak, T., Kotowicz, J., Węcel, D. (2008). Experimental and numerical investigations of the averaging Pitot tube and analysis of installation effects on the flow coefficient. *Flow Measurement and Instrumentation*, 19, 301–306.

[3] Dobrowolski, B., Kabaciński, M., Pospolita, J. (2005). A mathematical model of the self-averaging Pitot tube A mathematical model of a flow sensor. *Flow Measurement and Instrumentation*, 16, 251–265.

[4] Etemad, S.G., Thibault, J., Hashemabadi, S.H. (2003). Calculation of the Pitot tube correction factor for Newtonian and non- Newtonian fluids. *ISA Transactions*, 42, 505–512.

[5] *http://www.allpronix.com/wp-content/uploads/2015/08/ba_ibr_ibf_en.pdf* (Sep. 2015).

[6] *http://www.fayin.com.tw/polysonicsdatasheets/model_ssk1000.pdf* (Sep. 2015).

[7] *http://www.mesure.com/docs/Ellipse.pdf* (Sep. 2015).

[8] *http://www.testequipmentdepot.com/meriam/pdf/accutube_series.pdf* (Sep. 2015).

[9] *http://www2.emersonprocess.com/siteadmincenter/pm%20rosemount%20documents/00803-0100-6113.pdf* (Sep. 2015).

[10] ISO 3966. (2008). Measurement of fluid flow in closed conduits – Velocity area method using Pitot static tubes.

[11] ISO 5167-1. (2003). Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full – Part 1: General principles and requirements.

[12] ISO 5221. (1984). Air distribution and air diffusion – Rules to methods of measuring air flow rate in an air handling duct.

[13] Kabaciński, M., Pawliczek, R. (2012). Fully automated system for air velocity profile measurement. *The Archive of Mechanical Engineering*, 59(4), 435–451.

[14] Kabaciński, M., Pospolita, J. (2008). Numerical and experimental research on new cross-sections of averaging Pitot tubes. *Flow Measurement and Instrumentation*, 19, 17–27.

[15] Kabaciński, M., Pospolita, J. (2011). Experimental research into a new design of flow – averaging tube. *Flow Measurement and Instrumentation*, 22, 421–427.

[16] Kotzé, R., Wiklund, J., Haldenwang, R., Fester, V. (2011). Measurement and analysis of flow behavior in complex geometries using the Ultrasonic Velocity Profiling (UVP) technique. *Flow Measurement and Instrumentation*, 22, 110–119.

[17] Kring, J., Travis, J. (2006). LabVIEW for Everyone: Graphical Programming Made Easy and Fun. *National Instruments Virtual Instrumentation Series.*

[18] Kumar, P., Wong Ming Bing, M. (2011). A CFD study of low pressure wet gas metering using slotted orifice meters. *Flow Measurement and Instrumentation*, 22, 33–42.

[19] Kuznetsov, A.V. (2004). Numerical modeling of turbulent flow in a composite porous/fluid duct utilizing a two- layer k-ε model to account for interface roughness. *International Journal of Thermal Sciences*, 43, 1047–1056.

[20] Ostrowski, P., Remiorz, L. (2013). Measurement of gas flow in short ducts, also rectangular. *Flow Measurement and Instrumentation*, 30, 1–9.

[21] Pochwała, S., Kabaciński, M., Pospolita. J. (2012). Influence of typical flow disturbing elements on the flow rate in selected averaging Pitot tubes. *Task Quaterly*, 3–4, 219–228.

[22] Spitzer, D.W. (1991). Flow Measurement: practical guides for measurement and control. *ISA Research Triangle Park.*

[23] Turkowski, M., Szufleński, P. (2013). New criteria for the experimental validation of CFD simulations. *Flow Measurement and Instrumentation*, 34, 1–10.

[24] Vinod, V., Chandran, T., Padmakumar, G., Rajan, K.K. (2012). Calibration of an averaging pitot tube by numerical simulations. *Flow Measurement and Instrumentation*, 24, 26–28.

[25] Waluś, S. (2000). Decreasing of volume flow-rate measurement error in modified averaging impact tubes. *FLOMEKO 2000 International Conference on Flow Measurement*, Salvador, Brazil, FLOMEKO 2000 CD-ROM, B2.