Mirosław KABACIŃSKI
DEPARTMENT OF THERMAL ENGINEERING AND INDUSTRIAL FACILITIES, OPOLE UNIVERSITY OF TECHNOLOGY,
Mikołajczyka 5, 45-271 Opole, Poland

Influence of disturbed flow after an elbow on metrological properties of a Flow Averaging Tube

Abstract

Experimental results of air velocity profiles and Flow Averaging Tubes (FAT®) *K*-factor measured behind an elbow are presented in this paper. The pipeline diameter was *D*=150 mm, while the range of mean velocities *w*=9…30 m/s. Velocity profiles were determined both in the vertical and horizontal plane in the respective distances *L/D* of a pipeline from 3 to 18. In the places of the measured velocity profiles, three cross-sections of flow averaging tubes (circular, streamlined and two-profile) were placed to determine the characteristics of *K*-factor. Moreover, a fully automated test stand is presented in this paper. The completed experiment allows shortening the distance between an elbow and a flowmeter installation place and informing about the value of a correction factor, which can be used to minimize the measurement uncertainty of the air flow rate. It was stated that the horizontal plane is better to install a probe because of the velocity profile and better results of repeatability.

Keywords: velocity profile measurement system, averaging Pitot tube, Flow Averaging Tube K-factor, elbow flow, automated test stand.

1. Introduction

Flow measurements for gases and liquids in industrial conditions depending on numerous factors may be made using various flowmeters [1, 2, 3]. Many measuring devices cannot be used in high pressure and high temperature conditions [3]. Differential pressure flowmeters constitute a group of measuring devices which, as only few, are fitted for the use in these conditions [4, 5]. Besides orifices, they include Flow Averaging Tubes [6, 7, 8]. The differential pressure method involves high permanent pressure losses and considerable flow system modernisations connected with flowmeter overall dimensions. Probes averaging dynamic pressure have no disadvantages of this sort [9]. While ensuring the required minimum pressure difference during flow measurement (Δp>100 Pa), they may successfully replace differential pressure flowmeters. Moreover, lower installation cost and simple fitting procedure for this flowmeter, significantly lower permanent pressure losses caused by their presence, and possibility of fitting and removal while the system is in service (the WET-TAP® system) incline to using them in place of orifices [10, 11].

Fig. 1 shows the principle of operation of a flowmeter with averaging Pitot tube (FAT®) and basic flowmeter components.

When it comes across a local obstacle in the form of a probe, the flowing fluid lips it causing local stream stagnation – overpressure p^+ on the inflow side. The reference pressure (underpressure) p^- may be taken from back or side walls. The measured pressure difference $\Delta p = p^+ - p^-$ (at known fluid density ρ, pipeline cross-sectional area A and the value of flow coefficient K) allows determining the mass flow rate q_m of flowing fluid:

$$q_m = A \cdot K \sqrt{2\Delta p \cdot \rho} \ . \tag{1}$$

The formula shown above may be applied when the velocity profile is formed [10-12]. In the case of local obstacles in the form of elbows, valves, dampers, diffusers or confusor converging cones, it becomes disturbed [13-15]. Then, it is difficult to determine the average velocity in a pipeline on the basis of flow section division into equivalent rings [1, 16] (their positions determine locations for receiving pressure with the help of impulse holes in the FAT®-type probe). It is important to determine velocity profiles at different distances behind a flow-disturbing element and the effect of the disturbed velocity profile on the value of the flow coefficient K of the probe [14, 17].

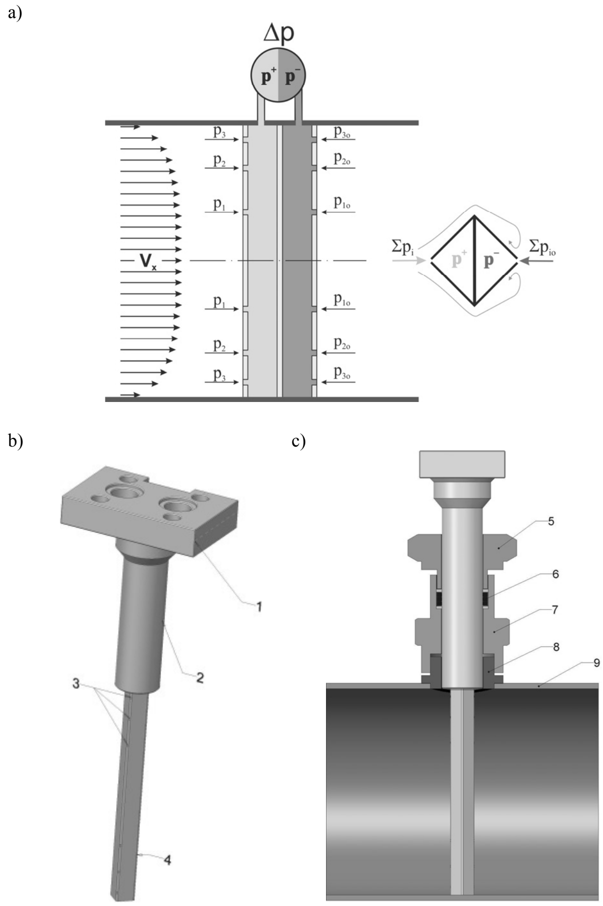


Fig. 1. Flowmeter with the FAT: a) principle of operation; b) particular elements: 1 - head, 2 – cylindrical part (mounted in choke), 3 – impulse holes, 4 – FAT®; c) choke fittings in the pipeline: 5 – nut, 6 – seal packet, 7 – choke, 8 – spout, 9 – pipeline

The recommended length of pipeline straight sections before and after a flowmeter is specified by flowmeter manufacturers in the equipment engineering specification [10].

Depending on the arrangement of individual system components, on the basis of the performed tests, a manufacturer specifies the minimum lengths of straight sections before and after a flowmeter in order to ensure the favourable velocity profile. The length of these sections depends on a flow disturbance degree. This allows the correct operation of a specific type of the averaging Pitot tube while maintaining the declared uncertainty of fluid stream measurement [18]. The length of straight section before a flowmeter may be reduced in certain conditions without using a flow straightener [14]. One should then carry out an analysis of impact of a non-standard installation place on an additional measurement uncertainty. Therefore, it is necessary to determine velocity profiles [19-23], especially in the immediate vicinity of a local obstacle [7, 24]. Then, it is required to make characteristics of the flow coefficient K for the examined Flow Averaging Tubes® in the areas of disturbed velocity profile in different pipeline sections [14, 15].

2. Experimental test stand

The measurements were carried out on a laboratory stand equipped with a disturbing system in the form of an elbow with curvature radius R_c=1D and R_c=3D (Fig. 2b and 2c, respectively) and internal diameter 150 mm. The medium was air with temperature ranging from 5 to 20°C, and pressure close to atmospheric. The detailed structure of an integral part of the measurement stand is shown schematically in Fig. 2.

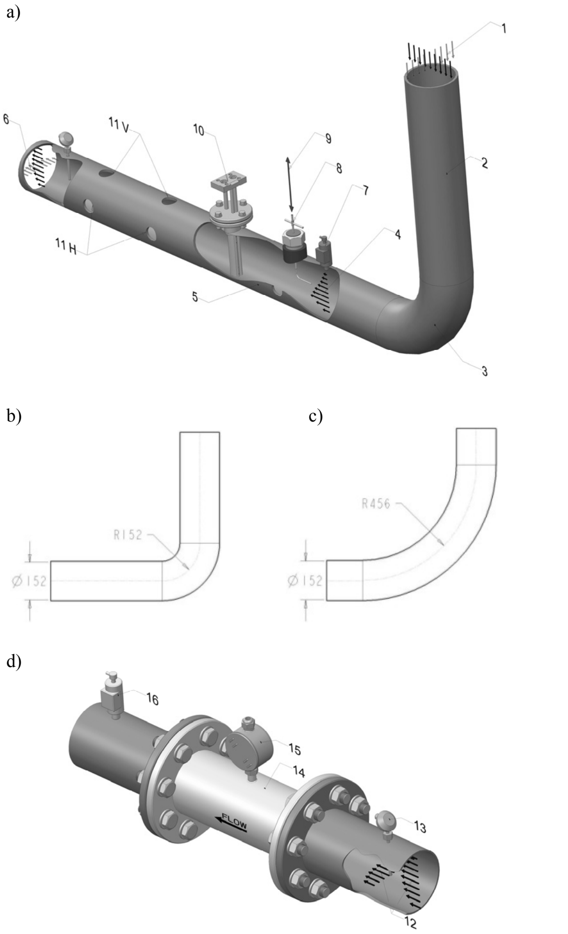


Fig. 2. a) Measurement system scheme: 1 – air inflow, 2 – velocity profile stabilizing section, 3 – elbow, 4 – disturbed velocity profile behind an elbow, 5 – test section, 6 – formed velocity profile at outflow, 7 – absolute pressure transducer, 8 – Prandtl tube, 9 – automatic shift – (see Fig. 4.8), 10 – tested FAT®, 11 – opening to measurement in vertical (V) and horizontal (H) plane; b) elbow with curvature radius R_c=1D, c) elbow with R_c=3D; d) System for average velocity determination in pipeline: 12 – parabolic velocity profile at inflow section, 13 – thermometer, 14 – turbine flowmeter, 15 – impulse amplifier + A/D converter, 16 – absolute pressure transducer

The test stand with measuring devices is shown in Fig. 3. Air flow in the measuring system was adjusted in a smooth way to reach the required values using a frequency converter working with a motor of centrifugal blower with max. flow rate 12 000 m^3/h. The average velocity of flowing air was determined using a reference method with the help of a high-performance turbine flowmeter 14 (Fig. 2d) 5 (Fig. 3) with accuracy under 0.5% of the measured value.

A system of two absolute pressure transducers and two Pt-100 thermometers was used for compensation in order to determine the average velocity in installation locations of the tested FAT® type flowmeters (Figs. 2a and 2d). This allowed entering the air density correction resulting from permanent pressure losses on the way from the examined differential pressure flowmeter to the reference (turbine) flowmeter. The pressure difference between the Prandtl tube and the tested averaging Pitot tube was measured using impulse wires by a differential pressure transducer integrated with a three-way block of valves 3 (Fig. 3).

The measurement stand was automated. Applications working in LabVIEW environment were developed for the purposes of measurement execution and measurement data acquisition (Fig. 4).

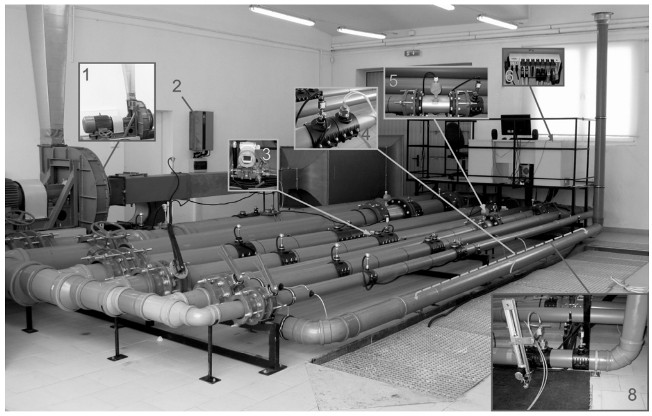


Fig. 3. General view of the test stand: 1 – centrifugal blower (q_{vmax}=12 000 m^3/h), 2 – frequency transmitter, 3 – differential pressure transducer with a block of valves, 4 – flowmeter with FAT® and absolute pressure transducer, 5 – turbine flowmeter, 6 – measurement cards in CompactDAQ system, 7 – test section, 8 – measurement system for velocity profile determination

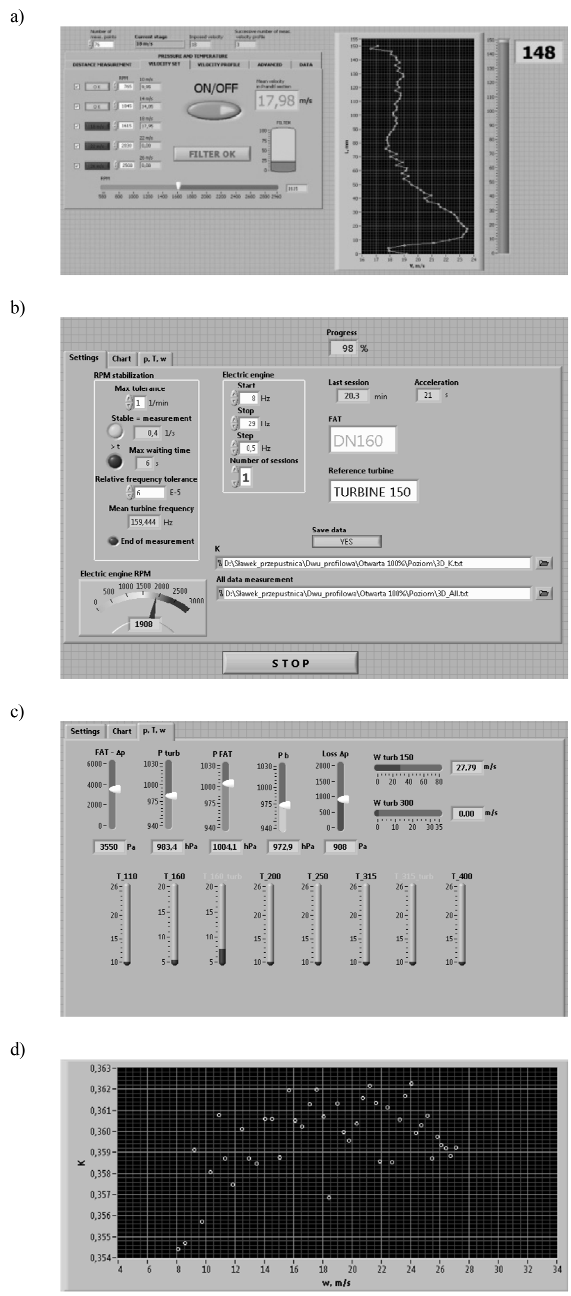


Fig. 4. Panel of the acquisition data computer program: a) for velocity profile measurement, b) - d) for K-factor determination

The first application (Fig. 4a) was intended to maintain one of five preset average flow velocities in the velocity profile test point and to move the Prandtl tube to proper positions in a pipeline cross-section. Owing to this, it was possible to determine the velocity profile in the pipeline (based on a specific number of measurement points) and to make its graphic interpretation in real time for a given average velocity.

The second application (Fig. 4b - d) allowed determining characteristics of the *K* flow coefficient as a function of the average velocity for the averaging Pitot tube. The measurement results from all the sensors were processed and changed into appropriate parameters after scaling (e.g. current into pressure or resistance into temperature), converted using appropriate functions into target parameters (e.g. average velocity of flow, flow ratio, blower motor speed), and then archived in the form of files for each measuring session. Electric signals from the measuring devices were transmitted to a computer via measuring cards integrated in the CompactDAQ system (Fig. 3.6). The following signals were measured:

1. Current - measurements of absolute pressure, differential pressure and control of blower motor speed,
2. Frequency - determination of average velocity using turbine flowmeter,
3. Resistance - temperature measurements,
4. Digital - control of Prandtl tube position while determining velocity profile.

3. Experimental results

3.1. Velocity profiles in selected system locations

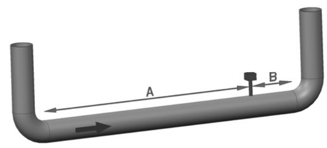
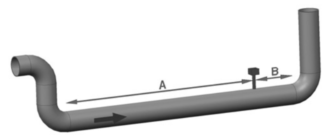
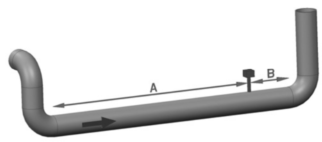
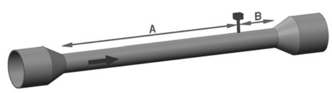
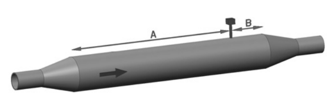
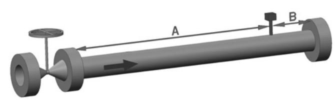
Experimental research was started from determining velocity profiles in selected cross-sections after the elbow (3, 4, 5, 6, 7, 8, 9, 10, 12, 14 and 18) for three velocities form the following ranges: 10 m/s, 18 m/s, and 26 m/s. The measurements were made using the Prandtl tube in the vertical and horizontal plane in 73 spots spaced at the same distance (every 2 mm). The obtained results allowed preparing the characteristics of velocity profiles in a function of the distance after the *L/D* elbow for the horizontal and vertical plane for elbows with curvature radius R_c=1*D* and R_c=3*D*. Ultimately, 132 velocity profiles were obtained. Figs. 5 and 6 show examples of velocity profile characteristics, respectively for the vertical and horizontal plane (according to Fig. 2) for the average velocity *w*=18 m/s.

Value l appearing in the Y-axis description specifies the distance of the measurement point from the pipeline bottom (vertical plane) or the side wall (horizontal plane). The diagrams unequivocally prove that the air velocity profile stabilises at the distance of 10 to 12 *L/D* after the elbow. It is consistent with the requirements regarding lengths of straight lines after an elbow, shown in Tab. 1. The specified distance *L/D*=15 guarantees the velocity profile formed so as to ensure the flow measurement at the required uncertainty level ±1%, regardless of the elbow curvature definition, R_c.

While comparing the velocity profiles prepared for the vertical plane (Fig. 5), it is possible to observe significant impact of elbows on considerable deformation of the velocity profiles at the distance *L/D* < 12. Whereas, the differences resulting from the impact of elbow curvature radius R_c are visible in section *L/D* < 8 after the elbows (particularly characteristic are slightly higher fluid velocities at the distance of 10…20 mm from the pipeline wall).

In the case of horizontal plane (Fig. 6), elbow curvature impact is obvious. It is manifested by high velocity diversification in the profile and its irregularity in the case of an elbow with less curvature radius R_c, while the characteristics show a narrower velocity range near the pipeline axis. Both for vertical and horizontal plane, the elbow curvature impact is relatively small with increasing the distance from the elbows (*L/D*>12).

Tab. 1. Exemplary average lengths of pipelines before and after the FAT® for different flow systems [10]

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

3.2. Values of the flow coefficient K for probes in the case of shortening straight sections before the flowmeter

Characteristics of the flow coefficient *K* were determined for 3 different cross-sections of flowmeters at 11 distances after the elbow. For these locations, the velocity profiles (*L/D*=3…18) were determined earlier. Fig. 7 shows sensor cross-section dimensions in the plane of impulse holes.

The completed tests allowed obtaining eleven *K*-factor characteristics for the vertical and horizontal plane for each probe. Finally, 66 flow coefficient *K* characteristics were obtained in a function of the average velocity *w* (*Re* number) for 3 different measurement probes (Fig. 7) within the average velocity range from 9 m/s to 30 m/s ($Re = 9.05\times10^4 \ldots 3.02\times10^5$).

Fig. 8 shows exemplary values of the flow coefficient *K* for characteristic installation locations in the vertical plane. The *K*-factor characteristics were compared for each probe, taking into account the fitting method (vertical or horizontal) and elbow curvature R_c. The same value scales were used in the axis representing the *K*-factor value in order to make it easier to compare the curvature R_c impact on the shape of characteristics.

The *K*-factor characteristics for the probe with circular cross-section for the elbow with R_c=1 in the vertical plane (Fig. 8) are more distant from each other than in the case of the elbow with curvature R_c=3, whereas its value variability is similar in both cases.

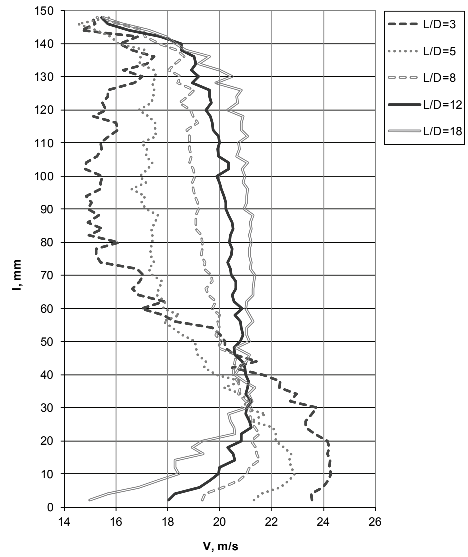
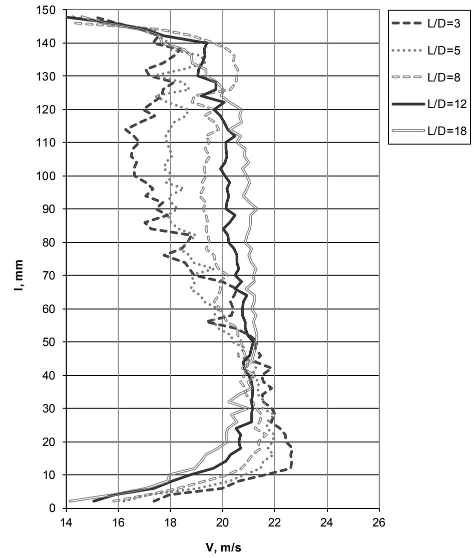
R_c=1D	R_c=3D
	

Fig. 5. Velocity profiles in selected places behind the elbow (vertical plane) at the mean velocity w = 18 m/s

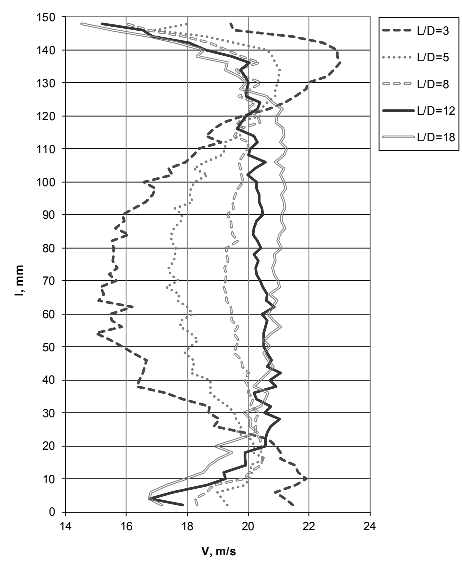
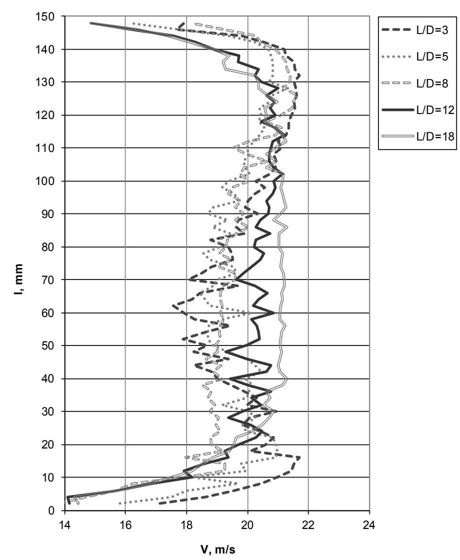
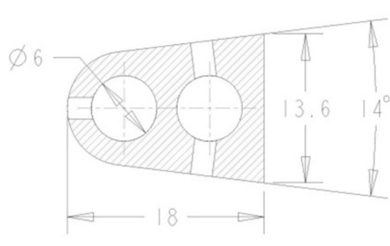
R_c=1D	R_c=3D
	

Fig. 6. Velocity profiles in selected places behind the elbow (horizontal plane) at the mean velocity w = 8 m/s

a)

b)



c)

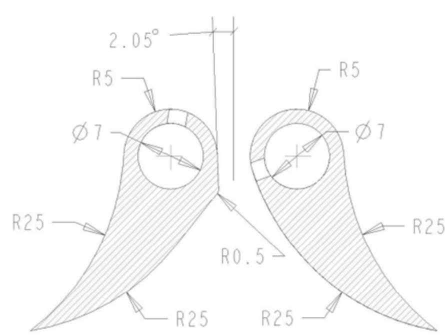


Fig. 7. Cross-section and characteristic dimensions of the tested averaging probes: a) circular cross–section probe, b) streamlined probe, c) two – profile probe

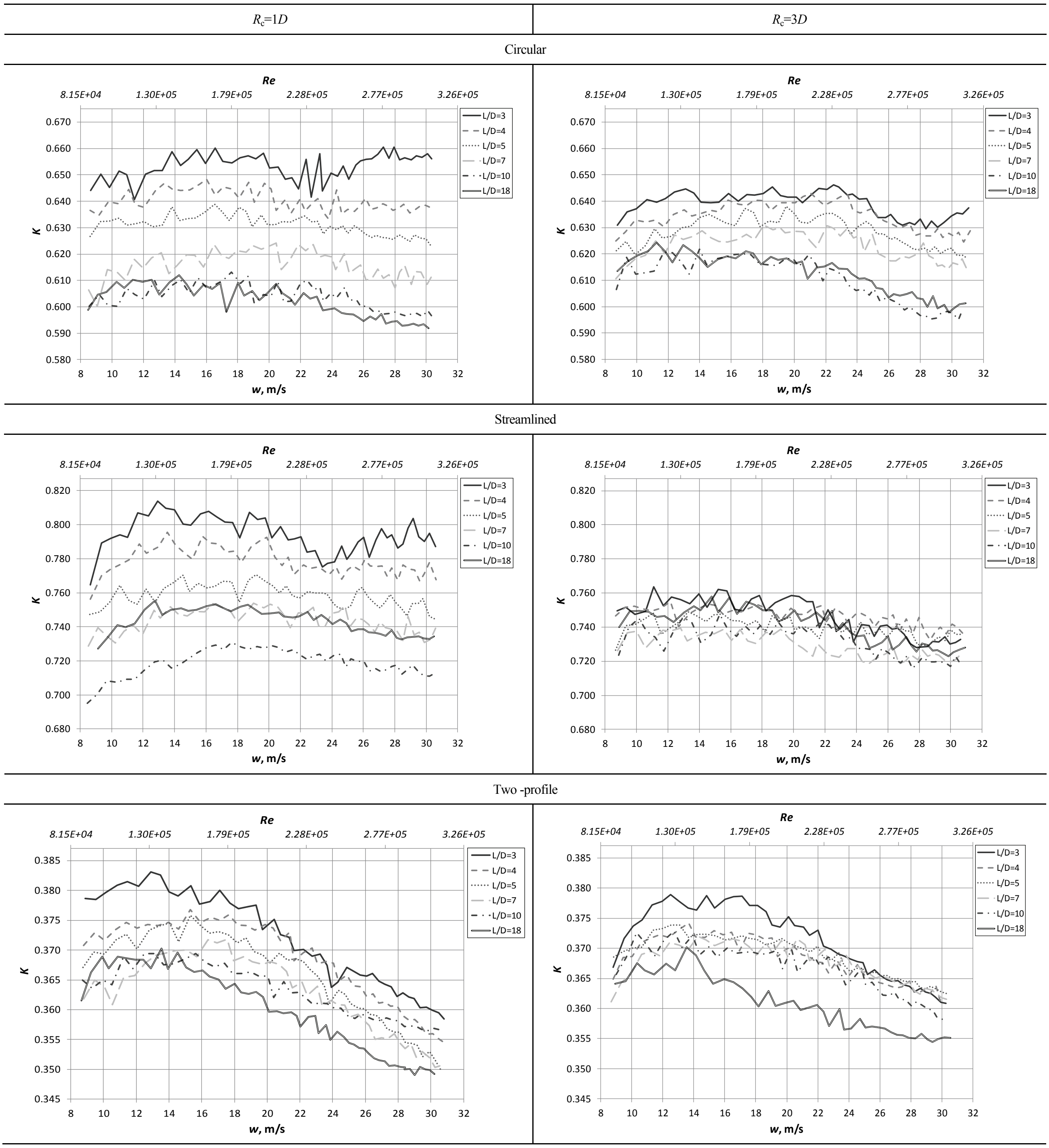


Fig. 8. Flow coefficient K values (vertical plane) as a function of the air mean velocity (Re number) for different cross-section of FAT®

In the case of a streamlined probe, the characteristics have much the same trajectories. Only for the elbow with smaller curvature radius they are more distant from each other (shifted as regards K value). An exception is the distance L/D=10, which shows the characteristic with lower values than the previous distance L/D=7, and the distance L/D=18 much farther away beyond that place. The reason for this may be the applied method of receiving pressure p^- from the side walls of the probe and the deformed (partially unsymmetrical) velocity profile. The further part of this work (Fig. 10) shows in detail the impact of the elbow on the K-factor value for this case (based on 11 measurement locations after the elbow). Similar tendency in the mentioned range appears for the elbow with radius R_c=3.

The K-factor values are considerably lower for the distances L/D=3…7 and for all the characteristics they fit within a much narrower value range: K=0.740 ± 0.02.

The two-profile probe generates the highest differential pressure Δp, and therefore the K-factor value is the lowest. These characteristics have tendency to reduce the K-factor value at higher velocities due to greater permanent pressure losses caused by the presence of the flowmeter installed in the pipeline with lower diameter (D=150 mm). There is no significant difference visible in the characteristics for both elbow cases, with the exception of overlapping, and at the same time flatter characteristics for L/D=4…10 at R_c=3.

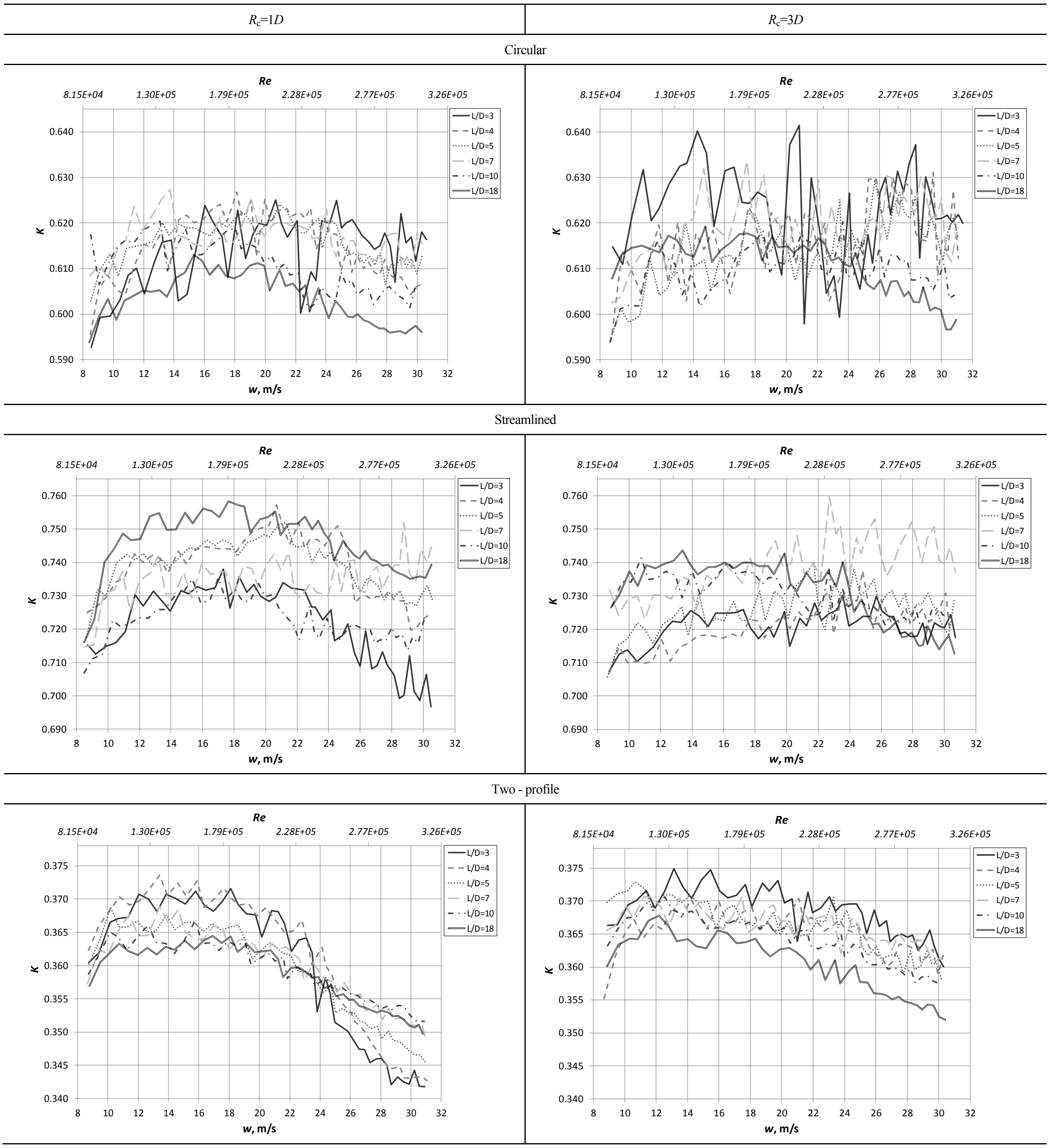


Fig. 9. Flow coefficient *K* values (horizontal plane) as a function of the air mean velocity (*Re* number) for different cross-section of FAT®

Fig. 9. shows the *K*-factor characteristics for the horizontal position of the flowmeters (perpendicular to the elbow plane). In the case of the probe with circular cross-section and the streamlined probe, their characteristics are flatter (after taking into account a modified scale on the Y-axis for the *K*-factor values). Changes in the characteristics for the streamlined probe, where *K*=0.700 … 0.760 are particularly visible. In the case of this probe, the minimum *K*-factor values were obtained for the smallest distance from the elbow (*L/D*=3), contrary to the tests performed in the vertical plane.

For the cylindrical probe, in the case of measurements close to the elbows, the characteristics are highly irregular and from metrological point of view difficult to approve. This is connected with an additional measurement uncertainty resulting from dispersion of the points in the characteristic reaching even ±3%.

The most favourable characteristics, relatively flat and slightly differing from each other, are shown by the two-profile probe for the elbow with radius curvature R_c=3*D*. In the case of the elbow with smaller curvature, trajectories of characteristics for the distances ranging from *L/D*=3 to 10 show dropping tendency for higher velocities.

For comparative purposes, the characteristics of the flow coefficient in a function of the distance after the elbow (Fig. 9) were prepared, both for the vertical and horizontal plane.

Fig. 10 shows cumulative *K*-factor characteristics for 3 sections of probes damming up flow. The solid line connects the averaged values of the *K*-factor determined in 11 locations after the elbow, for the vertical (triangular marker) and horizontal plane (circular marker), respectively.

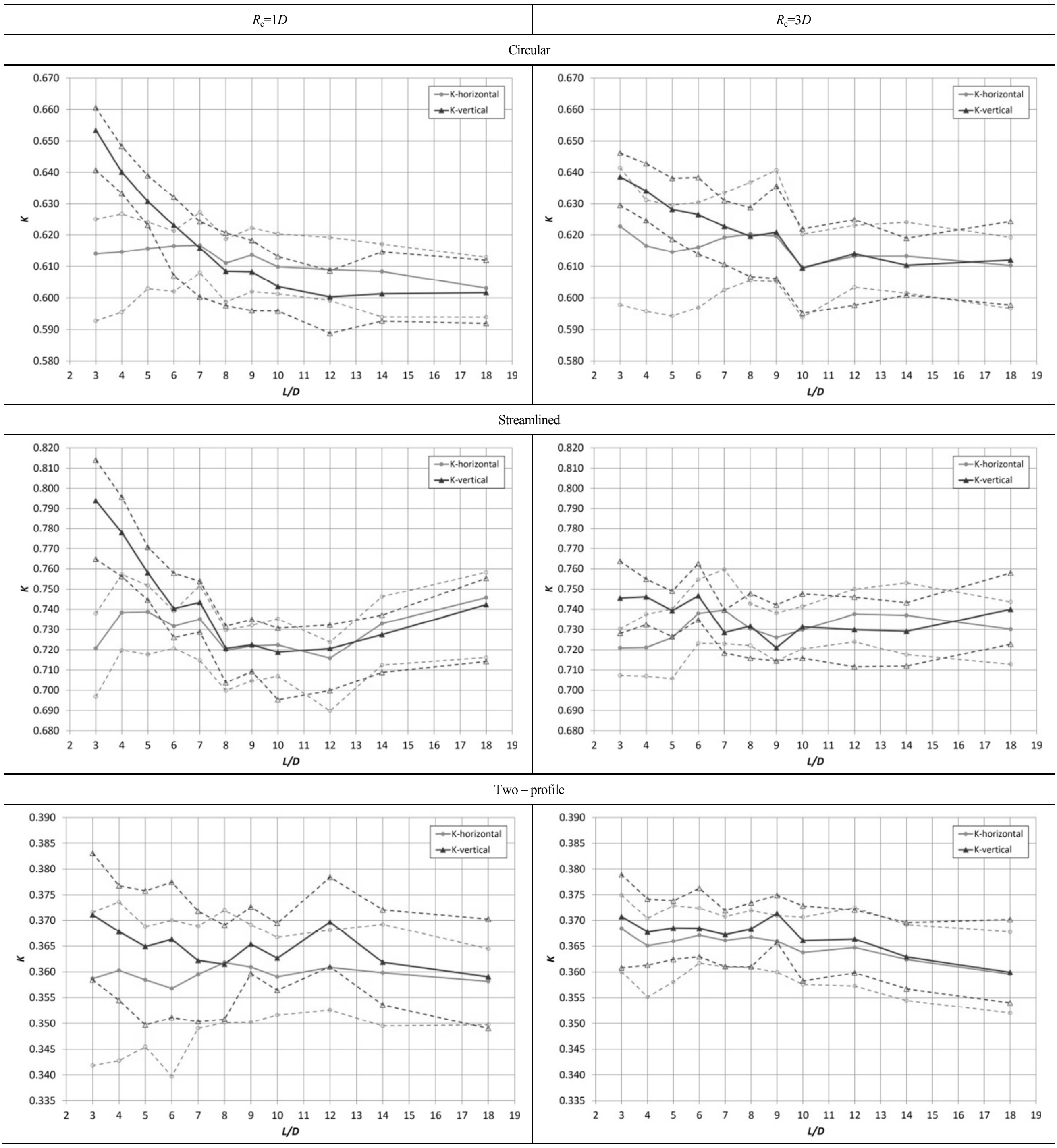


Fig. 10. Comparison of the flow coefficient *K* values for both vertical and horizontal plane (mean values depicted as solid lines but min and max values as dashed lines). Characteristics were prepared as a function of the distance between the elbow (*L/D*) and the place of installation of different probes cross-sections

Whereas, the broken line connects the minimum and maximum values, respectively. This allowed obtaining intervals of *K*-factor occurrence for each *L/D* location and fitting direction (H or V) after the elbow within the range of the considered *Re* numbers after flowmeter installation in the location nearer the elbow than recommended by the manufacturer. Diagrams shown in Fig. 10 allow concluding that a smaller distance past the elbow gives a higher *K*-factor value (especially for R_c=1). This phenomenon is particularly characteristic for the probe with circular and streamlined cross-section.

Higher variability of the average *K* values while moving away from the elbow is observable in the case of the elbow curvature plane (vertical). This has been already described in the analysis shown in Figs. 8 and 9. The two-profile probe is least sensitive to change in location, fitting direction (H or V) and elbow curvature R_c.

Information provided in Fig. 10 may be used when making decisions concerning flowmeter installation in an untypical location (not anticipated by a manufacturer), where the required length of straight sections (*L/D*) after an elbow is smaller than that given in Tab. 1.

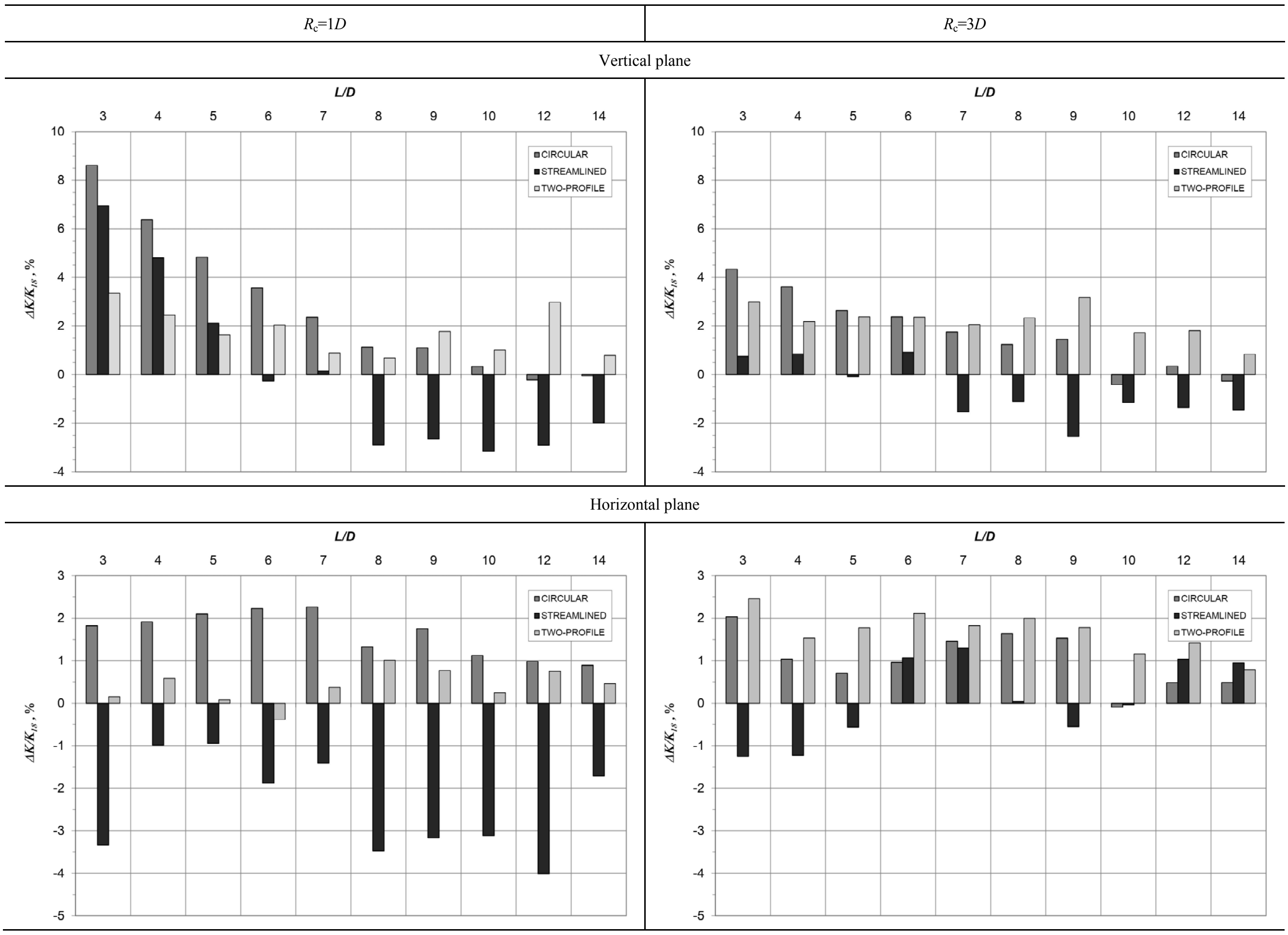


Fig. 11. Flow coefficient values change $\Delta K/K_{18}$ (referred to K in L/D = 18 location) as a function of the flowmeter location L/D behind the elbow

4. Influence of velocity profile on the probe K-factor

Having the value of the flow coefficient K, it is assumed that its value remains at much the same level within the range specified by the flowmeter manufacturer in its engineering specifications. Values shown in the bar graph (Fig. 11) allow entering correction of the flow coefficient K value depending on the flowmeter probe position (H or V) and the distance from the elbow (L/D).

The presented data unequivocally weigh in favour of a device fitting in the plane perpendicular to the elbow curvature (H). In the horizontal plane, the K-factor values fluctuate to smaller extent, in a manner making it easier to introduce its modified value for a wider range of L/D distances. It results from the velocity profiles, which maintain similar axial symmetry, especially near the elbow (Fig. 6). And thus, for example: on average, the K-factor values for the probe with circular cross-section (vertical plane, R_c=1) are larger by 1.64% compared to the K_{18} factor determined at the distance approved by the probe manufacturer. Entering the correction coefficient having this value will allow obtaining the uncertainty of K-factor determination at the average level of ±0.75% for a wide range of distances; from L/D = 3 to 14. On the other hand, in the same conditions, the streamlined probe shows considerably lower K-factor values with relation to K_{18} (from –1% to –4%). Entering the correction coefficient of 2.4% will reduce the uncertainty interval for K-factor determination within ±1.6% for the whole range of distances below L/D = 14. Certainly, the most accurate from metrological point of view will be to apply a correction coefficient chosen for specific location and position of a flowmeter, without averaging for a wide L/D range.

The two-profile flowmeter seems to be the most advantageous, regardless of fitting position and curvature radius Rc. In the case of the horizontal plane (for Rc=1D), the K-factor value without correction stays within ±1%, whereas for the same elbow and vertical plane after entering the correction of −1.6%, the K-factor value will not be higher than ±1% for distances ranging from L/D = 4 to 14.

5. Summary

The experimental tests performed on the demonstrated test stand allowed determining velocity distributions for flowing air after the elbow with curvature radius R_c=1D and R_c=3D within the average velocity range 9÷31 m/s (Re=9.36·10^4…3.22·10^5) in the pipeline with diameter 150 mm. Velocity profiles both for vertical (elbow curvature plane) and horizontal plane (plane perpendicular to elbow curvature) were obtained for 11 distances ranging from L/D = 3 to 18. The measurement results proved advisability of fitting an averaging a Pitot tube in the plane of occurrence of axial velocity distribution symmetry (horizontal plane). In spite of the velocity distribution deformation in this plane, relatively low variability of the measured K - factor values is maintained within the distance range from L/D = 5 up to 14. Whereas in the vertical plane, the relationship between the K-factor value and the distance from the elbow is significantly less favourable (Fig. 11 for R_c=1D) and reaches up to 9% (circular probe) with relation to the distance of L/D = 18. Also, higher dispersion of the measurement results was observed for this plane, which translates directly into increasing the measurement uncertainty for the fluid stream.

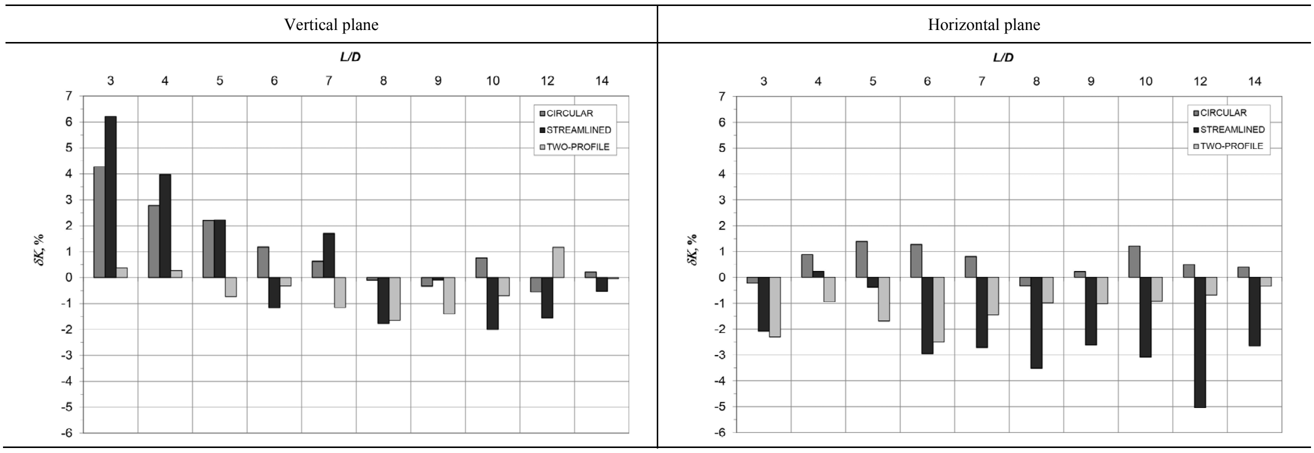


Fig. 12. *K*-factor comparison for the measurements behind the elbow of curvature radius 1*D* and 3*D* ($\delta K = K_{1D} - K_{3D}$)

The detailed flow coefficient *K* characteristics shown in Figs. 8 and 9, developed in a function of *Re* number, allow carrying out the thorough comparative analysis for different probe locations.

Information contained in Fig. 10 shows in a more transparent (simplified) way the averaged values of the *K*-factor for all the analysed distances after the elbow. In practice, it means that while designing or modernising the flow system it will be possible to make a decision concerning application of elbows with a suitable curvature radius, and selection of vertical or horizontal position for mounting a flowmeter.

Whereas in the existing system, it is possible to select the optimal probe fitting location, position and cross-section according to values shown in Fig. 9, taking into account the expected differential pressure Δp (no less than 100 Pa), especially in the case of flows characterised by smaller values of *Re* number.

After installing the selected flowmeter in a suitable location and position, it is possible to reduce significantly the measurement uncertainty for the measured stream by entering correction coefficients resulting directly from Fig. 11. These diagrams show the change in the *K*-factor value compared to the value specified by the manufacturer (determined at the distance of L/D>15). Application of the correction coefficient comes down to changing a sign of the value read out from the diagram, or in other words to subtracting this read out value from the initial value (K_{18}). Considering the fact that the relationship between the *K*-factor and measured stream q_m is directly proportional (Eq. 1), one may state that the correction introduced according to Fig. 11 will have direct influence on reduction in the measurement uncertainty for the flow rate.

Fig. 12 shows the impact of the elbow curvature on the *K*-factor value for the flowmeters installed in the same location and for the same fitting direction (V or H). The diagrams provide information, how much the *K*-factor value is higher or lower for the elbow with curvature radius R_c=1 with relation to the elbow with radius R_c=3. The figure unequivocally shows that the presented differential values are significant and should be taken into consideration. In practice, it may indicate that when changing an elbow in the system with another one, characterised by a different curvature radius (e.g. due to permanent pressure losses), other *K*-factor values should be introduced according to Fig. 11. Considering non-standard conditions for flowmeter building-in (L/D < 15) and visible changes in the coefficient *K* value in the case of modifying the elbow curvature R_c, it is required to apply in a strict manner correction coefficients taking into account: probe cross-section, pipeline internal diameter, fitting direction (H or V), and distance past elbow (L/D).

6. References

[1] Pospolita J.: Fluid stream measurements. Studies and Monographs, Opole University of Technology, vol. 154, Opole, 2004, p. 282.

[2] Kabza Z.: Fluid stream measurements, Studies and Monographs, vol. 90, WSI, Opole 1996.

[3] Kucybała A.: To select right flowmeter, PAR, 4/2002, p. 16-18.

[4] ISO/TR 15377:2007: Measurement of fluid flow by means of pressure-differential devices - Guidelines for the specification of orifice plates, nozzles and Venturi tubes beyond the scope of ISO 5167.

[5] PN-EN ISO 5167:2005: Fluid stream measurements carried out using measuring tubes incorporated in entirely filled up pipelines with circular cross-sections.

[6] Kabaciński M., Pospolita J.: Experimental research into a new design of flow-averaging tube. Flow Measurement and Instrumentation, vol. 22, 2011, pp. 421-427.

[7] Kabaciński M.: Experimental Research on Velocity Profiles in Selected Flow Systems TASK Quarterly, 3-4/2012, pp. 185-201.

[8] Kabaciński M., Pospolita J.: Numerical and experimental research on new cross-sections of averaging Pitot tubes, Flow Measurement and Instrumentation, vol. 19, No 1, 2008, pp. 17-27.

[9] Kabaciński M.: Numerical and experimental research on a new design of averaging Pitot tube, Doctoral Dissertation, Opole University of Technology, Opole, 2004.

[10] Introbar– flowmeters with tubes averaging dynamic pressure. Engineering Specifications, Introl Katowice, 2006.

[11] Pospolita J.: Flowmeter with sensor averaging dynamic pressure – Research and Development Project PBR 0504/R/2/T02/07/02, Opole University of Technology, 2009.

[12] Annubar flowmeters, 2002, Catalogue Sheet 00813-0114-4809.

[13] Dobrowolski B., Kabza Z.: Theoretical analysis of the impact of axial-dynamic deformation of velocity field and stream swirl on metrological properties of measuring tubes. Studies and Monographs, Opole 1992.

[14] Kabaciński M., Pochwała S.: The impact of velocity profile deformation on flow coefficient value for flowmeter with tube averaging dynamic pressure (In Polish), Measurements Automatics Control, 2011, No. 2, pp. 157-160.

[15] Pochwała S., Kabaciński M., Pospolita J.: Influence of Typical Flow Disturbing Elements on the Flow Rate in Selected Averaging Pitot Tubes, TASK Quarterly, 3-4/2012, pp. 219-228.

[16] Waluś S.: Metrological optimisation of fluid stream measurement using sampling flowmeters. Monograph, Silesian University of Technology, Gliwice 2003.

[17] Węcel D., Chmielniak T., Kotowicz J.: Experimental and numerical investigations of the averaging Pitot tube and analysis of installation effects on the flow coefficient. Flow Measurement and Instrumentation, vol. 19, pp. 301-306, 2008.

[18] Bechtold Z.: About the reasons of measurement result inaccuracies for distribution of velocity and flow rate by means of averaging Pitot tubes, Nr 15, Studies and Materials No 11, Wrocław 1978, p. 25-34.

[19] Raišutis R.:, Investigation of the flow velocity profile in a metering section of an invasive ultrasonic flowmeter. Flow Measurement and Instrumentation, 2006, pp. 201-206.

[20] Takeda Y.: Velocity Profile Measurement by Ultrasonic Doppler Method. Experimental Thermal and Fluid Science, 1995, pp. 444-453.

[21] Obayashi H., Tasaka Y., Kon S., Takeda Y.: Velocity vector profile measurement using multiple ultrasonic transducers. Flow Measurement and Instrumentation, 2008, pp. 189–195.

[22] ISO 3966:2008: Measurement of fluid flow in closed conduits - Velocity area method using Pitot static tubes, 2008.

[23] Cierniak W.: Measurement of the average flow velocity with the Pitot-Prandtl tube, Archiving of Mining Sciences 48, 2003, pp. 415 – 424.

[24] Kabaciński M., Pawliczek R.: Fully automated system for air velocity profile measurement, Archive of Mechanical Engineering, 2012, pp. 435 – 451.

[25] Abhari Naji M., Ghodsian M., Vaghefi M., Panahpura N.: Experimental and numerical simulation of flow in a 90º bend. Flow Measurement and Instrumentation, 2010, vol. 21, pp. 292-298.

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Mirosław KABACIŃSKI, PhD, eng

Since 2004 employed at the Department of Thermal Engineering and Industrial Facilities of the Faculty of Mechanical Engineering of Opole University of Technology. His research work and scientific interests are focused on measurements of the flow of liquids in industrial systems by means of flowmeters with averaging dynamic pressure tubes – experimental investigations and numerical simulations with Ansys Fluent. Co-author of many publications related thematically with flowmeters with Pitot probes.

e-mail: m.kabacinski@po.opole.pl