

Mirosław KABACIŃSKI, Janusz POSPOLITA

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

Flow averaging tube geometry improvement for K -factor stability increase

Abstract

Fluid flow around two-profile averaging differential pressure sensor was investigated in this paper. Research concentrated particularly on fluid movement direction and velocity over the investigated flow sensor. Analysis was conducted experimentally in low velocity wind tunnel. Because of large number of measuring points placed very close to each other, it was decided that velocity profile measurement will be performed by means of fully automated test stand. Due to a recirculation of the stream in the vicinity of the probe tested in the wind tunnel, an original two-direction probe was used. A linear module with a stepper motor formed an integral part of the measurement system. The location of the measuring probe, the possibility of adjusting stream mean velocities and data acquisition was undertaken by means of a dedicated program. The above mentioned investigation method helped to improve the metrological properties of the flowmeter applying non symmetrical probe cross-section forced air stream to be redirected in the desired direction. This modification significantly increased K -factor value and stability of air flow through the contraction of the flowmeter.

Keywords: velocity profiles, air flow measurement, closed conduits, automated test stand, flow averaging Pitot tube.

1. Introduction

Flow averaging tubes (Fig. 1) along with their armature and differential pressure transducer are listed among differential pressure flowmeters. This group contains also other tube designs including measuring and slotted orifices, nozzles, as well as meters used for estimating local fluid velocities such as Prandtl and Pitot tubes (mainly used for velocity profile determination). Fig. 1 presents an example of a flow averaging tube and time averaged distribution of static pressure along its surface.

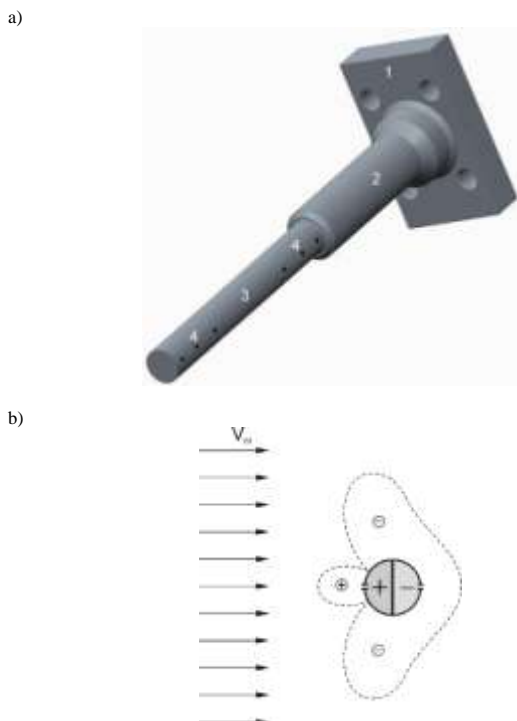


Fig. 1. Flowmeter with flow averaging tube: 1 – head, 2 – mounting, 3 – flow averaging tube, 4 – impulse holes; b) time averaged pressure area on tube and pressure tapping locations

This type of tubes has a number of advantages. In comparison to orifices, practically it is not observed significant permanent pressure losses. Besides, their installation is considerably cheaper and easier. The disadvantages are associated with relatively small values of the measured differential pressure (Δp) and intermittently variable motion of the fluid in the surrounding of the probe, which affects the pressures in the flow averaging chambers [11].

For the case of flow averaging tubes the relation between mean velocity of flow in the channel and the differential pressure Δp measured in the flow averaging chambers takes the form

$$V_m = K \sqrt{\frac{2\Delta p}{\rho}} \quad (1)$$

where ρ is the density of the fluid, and K – flow coefficient.

The flow averaging tubes applied in industrial practice have a wide range of engineering designs [1-4]. This concerns the shapes of the cross-section of the probe, the shape of the internal surface of the tube (flow averaging chambers) and the number and distribution of impulse holes along the side of inflow and outflow (side walls).

Exemplary values of K -factor and differential pressure Δp (for relatively low velocity) for common cross-section of flow averaging probes was shown in Tab.1. The problem is that possible low differential pressure could exceed about 150 Pa. Lower differential pressure makes impossible to measure fluid flows at low velocities.

Tab. 1. Flow coefficient K and differential pressure Δp for various cross-sections of flow averaging sensors for free air flow

Sensor's cross-section	K	Δp , Pa
		10 m/s
	~0.67	136
	~0.69	128
	~0.79	98
	~0.83	89

The authors have proposed a modernized design of the flow averaging tube (Fig. 2b) [5]. This decision was made after the analysis of the advantages and disadvantages of the parameters and requirements associated with them. The flow averaging tube presented in Fig. 2 offers relatively lower value of K -factor ($K \sim 0.62$, $\Delta p = 157$ Pa at 10 m/s) [5, 7].

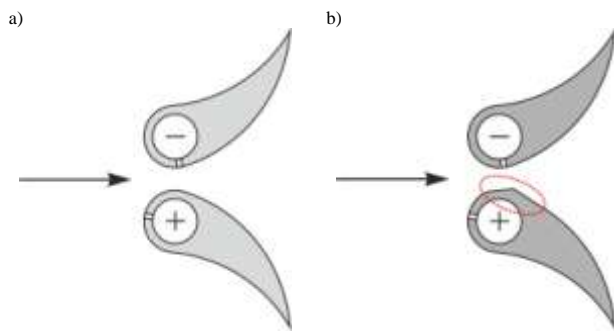


Fig. 2. Two-profile probe: a) symmetrical geometry, b) modified geometry (asymmetrical)

2. Research methods

A problem which needed to be solved was associated with the determination of an optimum distance between the profiles and their relative angle position (referred to dimension L). Concurrently, the determination of these quantities was necessary prior to the development of the engineering specification of the tubes and production of the prototypes.

The testing was undertaken in a wind tunnel [6, 7] which formed a part of the test stand presented in Fig. 3. This figure presents the manner in which they were installed in the test stand after their an appropriate location had been established.

One can note very clearly here that the characteristics presented in the Figs. 4 and 5 concern the testing in a wind tunnel. In the pipelines with the internal diameter of 0.1 to 0.3 m the two-profile probe has the value of the flow factor K in the range from 0.3 – 0.44 at the expense of generating larger permanent pressure losses.



Fig. 3. A crucial part of stand for flowmeter tests: 1-measurement part of wind tunnel, 2-linear module with stepper motor, 3- two-directional probe, 4-tested two-profile probe

The initial testing confirmed the beneficial characteristic of the flow averaging tubes. However, for some profile configurations it was observed that the K -factor changes its value stepwise by noting its 0.1 – 0.2 increase or decrease. By testing with a two-directional probe with a small diameter the flow behind the throat of the probe it was concluded that a recirculation is formed, which affects a change in the value of flow factor K depending on the location and direction of circulation. Fig. 4 presents the characteristics of this factor for symmetrical profiles. The value of the flow coefficient changes stepwise in the velocity range of 18 do 23 m/s. For the case of symmetrical profiles this phenomenon occurs in the entire range of the configurations of the distances and angles between the profiles in a manner which is difficult to

anticipate and register. From the view point of metrology such a property of a measurement device prevents its normal exploitation. In order to avoid this undesirable and random phenomenon, the geometry of the throat was modified to include a specific hump which imposes the flow of a stream in a specific direction. After a defined value of mutual angle position is exceeded, the mentioned above hump in a throat stops to play its role (for smaller fluid velocities in accordance with Fig. 4). This is caused by a stream separation along the wall surface on the side of the impulse hole in the underpressure profile.

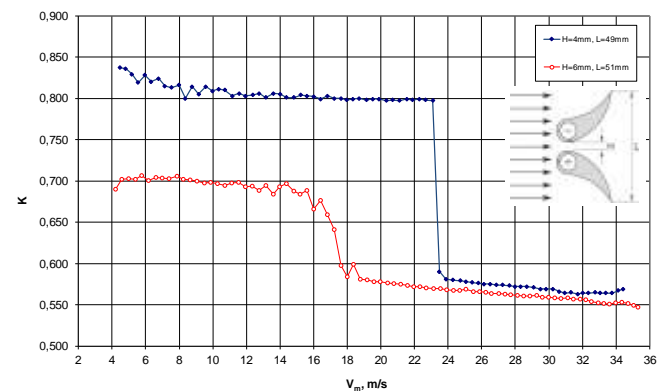


Fig. 4. Immediate change of K -factor value (symmetrical shape of probe cross-section)

The analysis of the initial results has encouraged authors to maintain the engineering change involving the application of a hump in the throat on the surface of the profile with the p^+ pressure measurement. This has brought the need to redirect the stream in the direction of the surface with the inflow pressure p^- . The modernization results of the one probe cross-section brought the results of better characteristics of flow coefficient K (Fig. 5). The optimum distance between two profiles are set to 44 mm. Larger distance L produces lower K -factor but its value is not stable in the whole range of velocities during tests (Fig. 5 - red line).

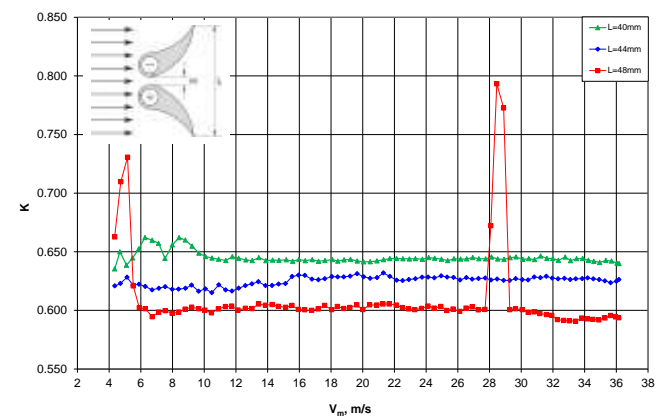


Fig. 5. K -factor characteristics for several configurations of mutual flowmeter profiles locations (asymmetrical shape of probe cross-section), $H=3mm$

The size, shape and location of the threshold were the subject of numerous tests and experiments. Subsequently, after the final determination of the tube profile, as demonstrated in Fig. 2, the profiles were made in accordance with the resulting data and parameters were tested in a wind tunnel. The results in the form of $K=f(w)$ characteristics for selected configurations of the profiles and p^- pressure tapping points are presented below.

The flow phenomena between and behind the profiles were found to be so interesting that the velocity profile was measured in the direction y (normal in relation to the plane of the tube location)

for several distances behind the probe throat. Two-directional probe (author's construction) was used for this purpose, as presented in Fig. 3.

3. Experimental results

The motion of the fluid, especially downward from the flow averaging tube, has unsteady character. The results of measurements presented in Figs. 6 and 7 are values averaged in time. The averaging was realized in the computer program working in LabVIEW environment [8].

Figs. 6 and 7 presents velocity distributions [9, 10, 12] behind the throat, for the distance $L=44$ mm, for mean velocity of the air inflow $w=10$ m/s and $w=18$ m/s. Locations are marked in the ordinate axis, in which the measurements were made (coordinates of the broken line). The velocity in the broken line is also marked in the ordinate axis. Its value for a given coordinate x is defined by the interval between the coordinate y marked by the solid and broken lines of a specific colour (style). For example: 40 mm distance (brown solid line) represents values of velocity which must be diminished of 40 m/s value thus for -60 mm (x -axis) we obtain finally 12 m/s (52 m/s $- 40$ m/s).

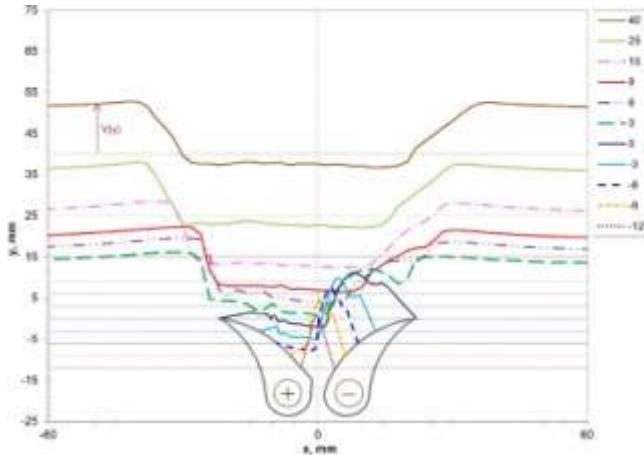


Fig. 6. A y-component velocity profiles behind the flowmeter throat ($L=44$ mm), $V_m=10$ m/s

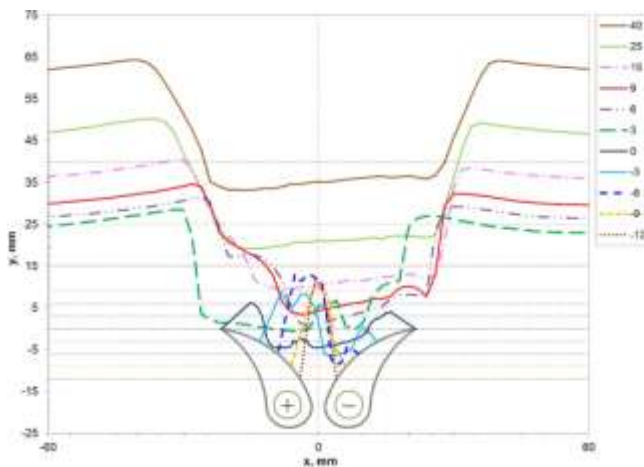


Fig. 7. A y-component velocity profiles behind the flowmeter throat (symmetrical shape of probe cross-section) for $V_m=18$ m/s and $L=44$ mm

Fig. 6 illustrates the effect of the asymmetry of the profiles on the motion of the medium. The stream is consistently directed at the profile with holes receiving underpressure (the one used to tap

pressure p^-). The negative values of the pressure in the probe throat on the side of the overpressure profile (the one used to tap overpressure p^+) demonstrate that a recirculation area exists in this section. Along with an increase of coordinate y the velocity of the air slightly decreases; thus, achieving the value corresponding to the velocity of air inflowing in the probe.

The data in Fig. 7 indicate that flow between two symmetrical profiles becoming more and more complex and the maximum V_y approaches the symmetry axis. This can also demonstrate a significantly non-stationary character of fluid flow.

In this case, the testing was performed for the mean velocity of inflowing stream of 18 m/s. These results are comparable to the results of measurement for a system with a hump, which are found in Fig. 7.

The complexity of the time averaged velocity profiles demonstrates the confirmation of high repeatability of the results obtained. Fig. 8 contains a comparison between the values measured in three series for mean velocity 18 m/s for symmetrical cross-section (more difficult case). This comparison indicates a very good repeatability of the results and, thus, provides information regarding good reliability of the measurements.

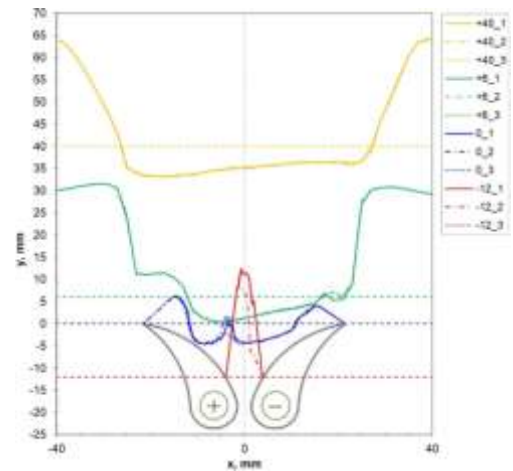


Fig. 8. Repeatability of experimental results (symmetrical shape of probe cross-section) for $V_m=18$ m/s and $L=44$ mm

The results of the measurements were applied and elaborated with regard to the fluid flow in the direction of the maximum value of velocity V_y 80 mm behind it. This direction was denoted as the main stream of fluid. The results of the measurement elaborated in this manner are presented for symmetrical profiles in Fig. 9, and for asymmetrical ones (including a hump) in Fig. 10.

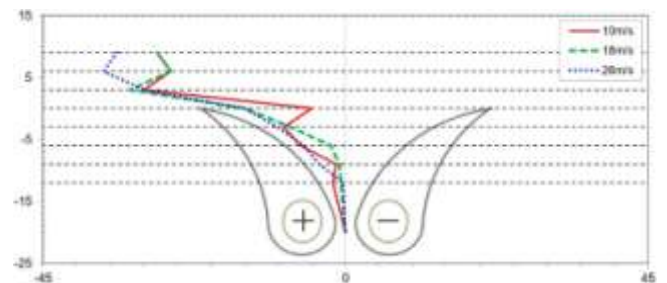


Fig. 9. Main fluid stream flows through the contraction on the base on y velocity component (V_y) for symmetrical geometry, $L=44$ mm

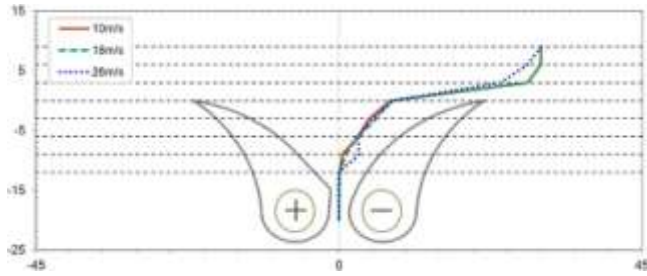


Fig. 10. Main fluid stream flows through the contraction on the base on y velocity component (V_y) for asymmetrical geometry, $L=44$ mm

For the case of symmetrical profiles the line which connects the points in which the maximum velocity occurs tends to change its direction abruptly between the specific locations (Fig. 10). For various velocities of fluid inflow on the tube do not lie close to each other. This is particularly visible for a probes with mutual angle set $L=44$ mm, which was adopted as the most appropriate one for the manufacture of the prototypes. The non-stationary motion of the fluid stream in the vicinity of the tube not only results in the abrupt changes in the flow factor K but also introduces non-linearity in the $K=f(\text{Re})$ characteristic. It can also form the reason for the lack of repeatability in the measured differential pressure. The repeatability of the measurement results presented in Fig. 10 justifies the adopted testing methodology. Concurrently, the differences in the time averaged velocity profiles amounting to several per cent may lead to 2% to 3% difference in the indications of the averaging tubes for the same mean velocity of the fluid. This, however, disqualifies this types of construction from further application, even in the application to assess metrological properties of the prototype design.

The data can be differently interpreted for the case of the velocity profile of a profile with a hump (Fig. 11). The motion of the fluid is unequivocally determined. The fluid passes smoothly in the direct vicinity of the profile with p^- pressure tapping. The repeatability concerns both the mean velocity of fluid inflow onto the probe and set of mutual angle position of the profiles.

4. Summary

This paper presents the results of research into the motion of fluid in the vicinity of a two-profile construction of a flow averaging probe. The testing involved flow averaging tubes with both two symmetrical and asymmetrical profiles. It was demonstrated through the research that for the case of symmetrical profiles the motion of fluid in the vicinity of the probe and downstream has a complex character. This results in abrupt and unpredictable fluctuations of the flow factor K . An additional hump installed in one of the profiles led to the stabilization of the fluid flow. In this case the fluid passes smoothly in the direct vicinity of the profile with p^- pressure tapping. The flow factor K for the profile with $L=44$ mm has a constant and repeatable value. The extensive testing undertaken in [7] indicated that the prototypes of probes with such a profile have very advantageous metrological properties of $K=f(\text{Re})$.

5. References

- [1] Dobrowolski B., Kabaciński M., Pospolita J.: A mathematical model of the self-averaging Pitot tube. A mathematical model of a flow sensor. *Flow Measurement and Instrumentation* vol. 16, issue 4, pp. 251-256, August 2005.
- [2] Accutube, Technical documentation, <http://www.accutube.com/>
- [3] Preso, Technical documentation, <http://www.preso.com/>
- [4] Veris, Technical documentation, <http://www.veris-inc.com/>
- [5] Mobrey, Technical documentation, <http://www.mobrey.com/>
- [6] Kabaciński M., Pospolita J.: Numerical and experimental research on new cross-sections of averaging Pitot tubes. *Flow Measurement and Instrumentation*, vol. 19, Number 1, pp. 17-27, March 2008.
- [7] Kabaciński M., Pospolita J.: Experimental research into a new design of flow-averaging tube. *Flow Measurement and Instrumentation*, vol. 22, 2011, pp. 421-427.
- [8] Kabaciński M., Pawliczek R.: Fully automated system for air velocity profile measurement. *The Archive of Mechanical Engineering*, Vol. LIX, No.4, 2012, pp.435-451.
- [9] Kabaciński M.: Experimental Research on Velocity Profiles in Selected Flow Systems *TASK Quarterly*, 3-4/2012, pp. 185-201.
- [10] ISO 3966:2008: Measurement of fluid flow in closed conduits - Velocity area method using Pitot static tubes, 2008.
- [11] Cierniak W.: Measurement of the average flow velocity with the Pitot-Prandtl tube. *Archiving of Mining Sciences* 48, 2003, pp. 415 - 424.
- [12] Obayashi H., Tasaka Y., Kon S., Takeda Y.: Velocity vector profile measurement using multiple ultrasonic transducers. *Flow Measurement and Instrumentation*, 2008, pp. 189-195.

Received: 02.10.2016

Paper reviewed

Accepted: 02.12.2016

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



Prof. Janusz POSPOLITA, DSc, eng.

He works at the Opole University of Technology. His research is concentrated on measurements in energetics. Author or co-author over one hundred scientific papers and many reports for industry referring to power boilers, coal pulverizers and measuring circuits. An author of the book "Measurement of fluid streams", published by Publishing House of the Opole UT (2008). In 2012-2016 vice-rector of the Opole UT. Now the dean of Mechanical Faculty of this University.

e-mail: j.pospolita@po.opole.pl

