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CFD Simulation and Experimental Study of Ultrasonic Flowmeters

Vitaliy Roman, Fedir Matiko, Roman Fedoryshyn
Lviv Polytechnic National University, Department of Automation of Heat and Chemical Processes,
Institute of Energy Engineering and Control Systems,
S. Bandery St. 12, Lviv, 79013, Ukraine,
e-mail: romanfedoryshyn@yahoo.com

This paper deals with CFD simulation and experimental study of ultrasonic flowmeters. A mathematical model of an ultrasonic flowmeter (USM) was built for studying the errors of flow measurement in disturbed flows. The method of defining the position coordinates of the acoustic paths and their weighting factors was improved based on the Gauss-Jacobi method of integration (i.e. the weighting function was improved) which provided the possibility to raise the accuracy of the turbulent flow velocity integration. The effectiveness of the improved method was verified using the Salami functions. New methodology for improving the mathematical model of USM is proposed. According to this methodology the dependence of the calibration factor on the Reynolds number is introduced into the model. A technique for studying the errors of USM in disturbed flows was developed on the basis of the proposed methodology. The developed technique was verified by comparing the CFD simulation results for a 3D model of an acting USM with the experimental results for this meter obtained by means of a reference test rig. The deviation of the simulation results from the obtained experimental data is not more than 1 %. Recommendations on defining the pipe straight lengths for the double-path chordal flowmeters were developed on the basis of the investigation results.

Keywords: ultrasonic flowmeter, mathematical model, flow rate, CFD, disturbed flow, error

Introduction

Ultrasonic methods and instrumentation for fluid flow rate and volume measurement are applied widely in various fields of industry including gas industry where natural gas metering is carried out during its transportation and supply to the consumers. The widespread application is caused by existence of new reliable ultrasonic flowmeters (USM) of gas providing high accuracy of measurement. For instance, multi-path USMs are developed for custody transfer of natural gas with the relative uncertainty of no more than ±0.15% (USZ 08 of Honeywell RMG Company), ±0.2% (FLOWSIC600 of SICK Company) or ±0.3% (Daniel Senior Sonic of Emerson Company).

It is known that the metrological characteristics of flowmeters depend on the operating conditions (in particular, on how much the operating conditions are different from the calibration conditions). Based on the numerous experimental studies [1-4] it was defined that the flow disturbances in the pipe upstream of the USM lead to significant errors in flow rate measurement.

To provide a fully developed flow profile without a flow conditioner the pipe straight length of up to 50*D* may be needed to eliminate an asymmetric profile or up to 200*D* to eliminate a flow swirl according to ISO 17089-1: 2010 [1]. Such long pipe straight lengths not always can be provided in operating conditions. That is why it is important to study the effect of a flow disturbance on the error of USM and to develop the up-to-date means for simulation in order to work out recommendations on installation of USMs to eliminate the additional errors of flow rate measurement caused by flow disturbances.

A powerful instrument for studying the gas dynamical processes in pipes together with experimental studies is a computer simulation by means of Computer Aided Design (CAD) and Computational Fluid Dynamics (CFD) software. The models of fluid flows in pipes of complicated configurations can be built by means of the software with high accuracy. These models provide the possibility to study the pipe configurations and USM constructions for which the experimental studies were not carried out sufficiently.

The results of CAD/CFD simulation for studying the effect of a disturbed flow on the error of USM are presented and discussed in works [2-7]. Based on the analysis of these works it was defined that there are a lot of CAD/CFD software types both with open access and with licenses. There are different constructions of pipe fittings and positions of acoustic paths of USMs. That is why there is a need to develop a generalized methodology for application of CAD/CFD software to improve the mathematical model of USM and to study the effect of a disturbed flow on the error of USM.

Mathematical model of a flowmeter

A mathematical model of an USM was built on the basis of the equation of volume flow rate for chordal multi-path configurations of meters [7] and on the basis of Gauss-Jacobi numerical method of integration [8]. According to this method of integration the position coordinates $x(i)$ of the acoustic paths are defined by solving the recurrent equation of the Jacobi polynomial [7,8]. The order of this polynomial is equal to the number of acoustic paths (*N*). After finding the position coordinates *x*(*i*), the weighting factors of the acoustic paths *w*(*i*) are defined by calculating the values of the Lagrange polynomial in the points *x*(*i*) and by applying a special formula for integration were the following weighting function of Jacobi polynomial is used

$$W(x)=(1-x^2)^k \tag{1}$$

where *x* is current radial position of an acoustic path, *k* is coefficient of weighting function.

The value of the coefficient *k* in the classical method is equal to 0.5 [8]. It is proposed to improve the method for defining the *w*(*i*) and *x*(*i*) of the acoustic paths of USM by improving the weighting function (1). The coefficient *k* of the weighting function is improved on the basis of comparison of *W*(*x*) values with the values of the power law of flow velocity distribution for a fully developed turbulent flow (see Figs. 1 and 2). The power law of flow velocity distribution in a relative form is presented by the following formula

$$\frac{v}{v_{\max}}=\left(1-\frac{r}{R}\right)^{\frac{1}{n}} \tag{2}$$

where *r* is current position along the pipe internal radius, *R* is pipe internal radius, *n* is Nikuradse number.

The Nikuradse number in (2) is defined as follows [9]

$$n=1/[0.2525-0.0229\lg(Re)] \tag{3}$$

where *Re* is Reynolds number.

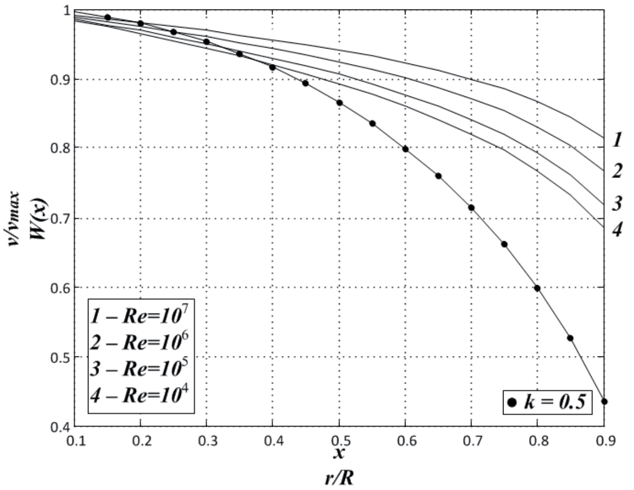

Figure 1. Comparison of the weighting function curve (–•–) for k=0.5 with the power law of flow velocity distribution (—)

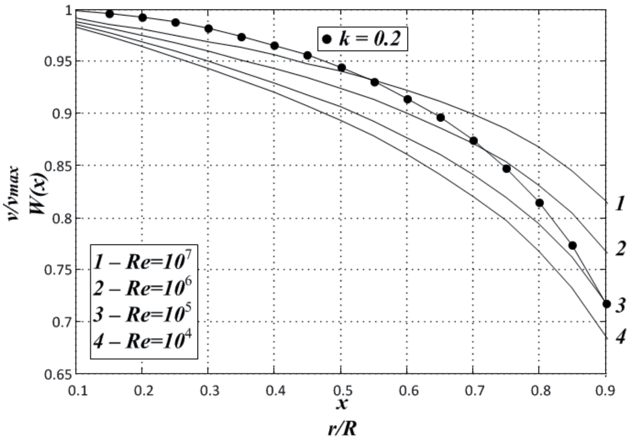

Figure 2. Comparison of the weighting function curve (–•–) for k=0.2 with the power law of flow velocity distribution (—)

It can be seen from Figs. 1 and 2 that for *k*=0.2 the weighting function curve is closer to the power law of flow velocity distribution than for *k*=0.5.

For a number of values of *k* the standard deviation of *W*(*x*) values from the values of the power law of flow velocity distribution were calculated for the values of *Re* from 10^4 to 10^7 and for the values of *x* from 0.1 to 0.9 [10]. Based on the calculation it was defined that the minimum standard deviation is reached for *k*=0.2.

The improved method for defining the *x*(*i*) and *w*(*i*) was also verified for a disturbed flow using the Salami function P09 [11]. The error of flow rate measurement result for a 4-paths chordal USM is reduced by 0.25 % when applying *k*=0.2 in comparison to *k*=0.5 (see Fig. 3). The error of flow rate measurement was calculated using the following formula

$$\delta_q=\frac{q_v-q_{v.Salami}}{q_{v.Salami}}\cdot 100 \tag{4}$$

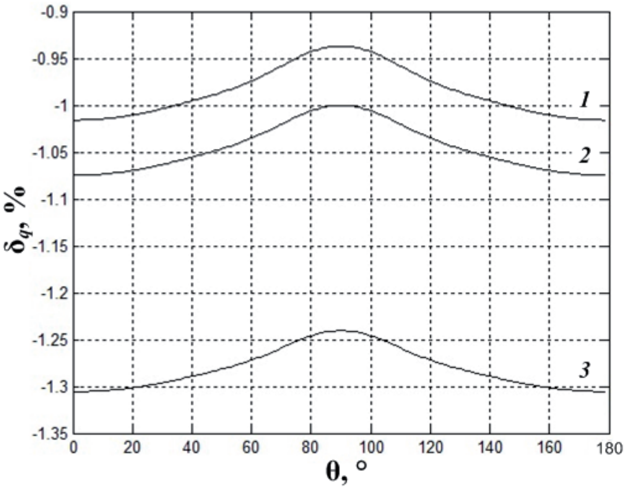

Figure 3. Flow rate measurement error versus integration angle for k=0.2 (curve 1), k=0.3 (curve 2) and k=0.5 (curve 3)

The mean flow velocities along each chordal acoustic path ($v_h(1)\ldots v_h(N)$) are the input variables of the mathematical model of USM. That is why the model can be applied together with a CAD/CFD software which provides the possibility to simulate the flow velocity profile and the mean flow velocities along each chordal acoustic path. The errors may take place during application of the mathematical model together with the CAD/CFD simulation software due to the following reasons.

1. Inaccurate drawing of the multi-path USMs and pipes which is caused by the complicated construction of the USM in the cases when the information on the geometrical dimensions of USM is absent or defined inaccurately (dimensions of the electro-acoustic transducers (EAT), their pockets, protection layer and length of the acoustic channel).
2. Inaccurate description of the behavior of the turbulent flow by the CAD/CFD software [3,6].

To eliminate the errors of USM simulation it is proposed to improve the mathematical model of the meter by introducing the dependence of the calibration factor on the Reynolds number $k_{cal} = f(Re)$ into the model [12]. The values of k_{cal} are defined on the basis of the reference values of volume flow rate ($q_{s.ref}$) and flow parameters derived experimentally for specific values of Reynolds number according to the following formula

$$k_{cal} = q_{s.ref} / q_s \tag{5}$$

The flow rate reduced to standard conditions is calculated as follows

$$q_s = q_v \frac{p_{CFD} T_s}{p_s T_{CFD} K(p_{CFD}, T_{CFD})} \tag{6}$$

where q_s is volume flow rate reduced to standard conditions, q_v is volume flow rate at operating conditions, p_s is pressure at standard conditions, T_s is temperature at standard conditions, p_{CFD} is fluid pressure for CFD simulation, T_{CFD} is fluid temperature for CFD simulation, K is fluid compressibility factor.

It should be stressed that the values of $q_{v.ref}$, p and T are used for setting the parameters of CFD simulation (boundary conditions) and the dependence $k_{cal} = f(Re)$ should be defined for an undisturbed flow.

Thus, the proposed methodology of improving the mathematical model of an USM consists in defining the dependence of k_{cal} on Re based on the results of CFD simulation and the available reference data on the measured flow rate and subsequent introduction of this dependence into the mathematical model. The generalized mathematical model of a multi-path USM with taking into account the proposed methodology and the improved method for defining the $x(i)$ and $w(i)$ is presented as follows

$$\begin{cases} q_v = k_{cal} \dfrac{\pi D^2}{4} \displaystyle\sum_{i=1}^{N} \dfrac{2\sqrt{R^2 - x(i)^2}}{\pi R} w(i) v_h(i); \\ k_{cal} = f(Re);\ Re_{\min} \le Re \le Re_{\max}; \\ k = 0.2;\ i = 1,\ 2, \ldots\ N; \\ w(i) = \dfrac{\displaystyle\int_{-R}^{+R} PL\big(x,\ x(i)\big)\big(1 - x^2\big)^k dx}{\big(1 - x(i)^2\big)^k}; \\ PL\big(x,\ x(i)\big) = \displaystyle\prod_{\substack{j=0 \\ j \ne i}}^{N} \left(\dfrac{x - x(j)}{x(i) - x(j)} \right); \\ PJ = f(x, N, k);\ x(i) = roots(PJ), \end{cases} \tag{7}$$

where D is pipe internal diameter, PL is Lagrange polynomial, PJ is Jacobi polynomial.

The mathematical model of USM (7) together with the CAD/CFD software provides the possibility to carry out simulation in order to study the effect of the constructional parameters of multi-path USMs as well as the effect of flow disturbance on the results of flow rate measurement.

Technique for studying the USM error

Technique for studying the error of flow rate measurement was developed on the basis of the mathematical model of USM (7). This technique is presented in [12] and it consists of the following steps:

1) definition of the main and supplementary constructional parameters of the USM and the pipe (see Fig. 4);
2) definition of the parameters of the fluid flow (type of fluid, flow rate, p and T etc.);
3) design of k_{cal} of USM model (drawing of 3D model of the USM and the pipe by mean of CAD software (see Fig. 5); setting of parameters of 3D model in CFD software; development of the dependence of k_{cal} on Re);
4) study of the USM error in a disturbed flow.

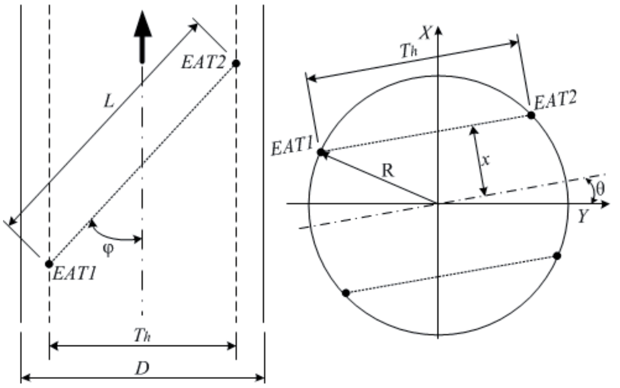

Figure 4. Simplified design diagram of a double-path chordal USM

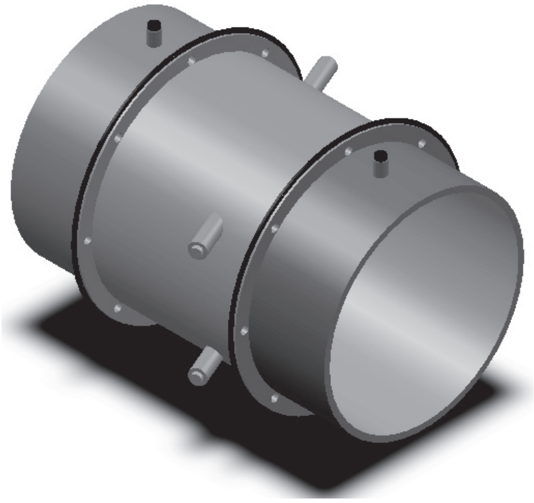

Figure 5. Three dimensional model of USM and pipe

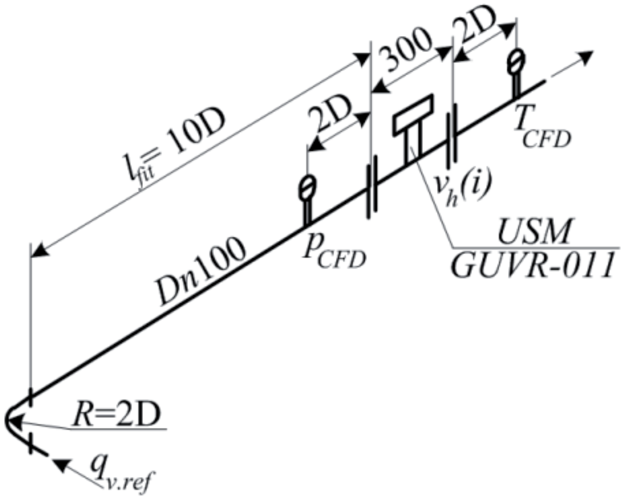

Figure 7. Axonometric diagram of pipe with USM installed downstream of a single 90° bend

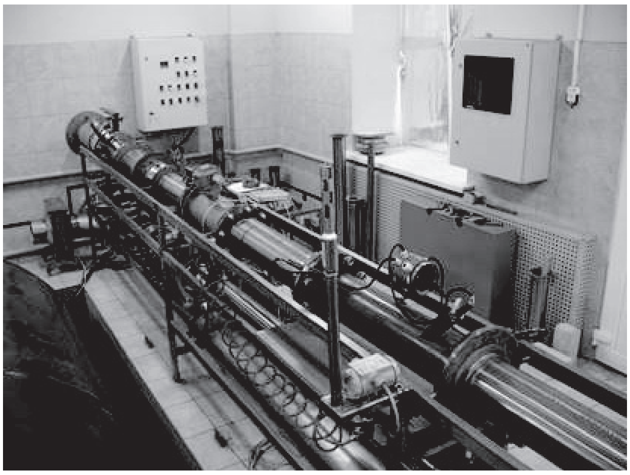

Figure 6. Picture of the test rig

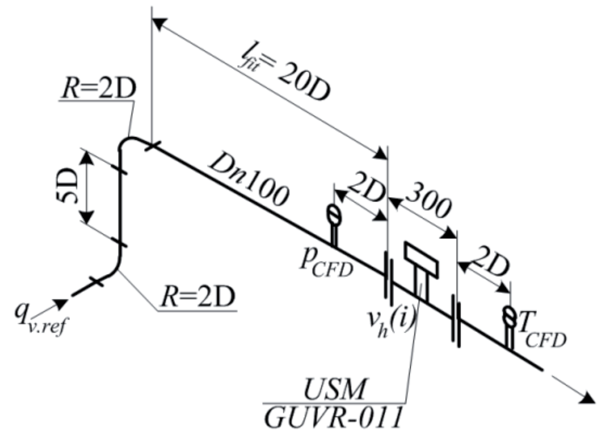

Figure 8. Axonometric diagram of pipe with USM installed downstream of two 90° bends in perpendicular planes (l≤5D)

The developed technique was verified on the basis of the results of experimental study of flow rate measurement error for an acting USM GUVR-011A2.2/VS in a gas test rig of "Energooblik" Company (Kharkiv, Ukraine) [12]. The working fluid was air. The picture of the test rig is presented in Fig. 6. It should be mentioned that both the experimental study and the simulation of USM were carried out without any flow conditioner according to the requirements specified by the flowmeter manufacturer in the operational documentation [13].

Three dimensional model of the USM (see Fig. 5) together with the pipe and the fittings was built by mean of CAD software. The pipe straight lengths were set according to the diagrams in Figs. 7 and 8. The simulated flow rate values were compared to the experimental results of flow rate measurement by means of the USM installed downstream of two typical fittings (single 90° bend, Fig. 7, and two 90° bends in perpendicular planes (l≤5D), Fig. 8). This way the conclusion about the adequacy of the proposed technique was made.

The mathematical model of the double-path chordal USM GUVR-011A2.2/VS (8) was built by means of the proposed methodology. This model was applied for calculating the flow rate measured by the flowmeters presented in Figs. 7 and 8. Here the values $q_{v.et}$ were taken equal to the experimental values of flow rate measured by the reference gas meter in the test rig.

$$\begin{cases} q_v = k_{cal}\dfrac{\pi D^2}{4}\dfrac{\sqrt{R^2-(0.5807R)^2}}{\pi R}[v_h(1)+v_h(2)]; \\ k_{cal} = \begin{cases} 38.79Re^{-0.7837} + \\ +1.01; \quad Re = 1\cdot 10^3 \div 5\cdot 10^3; \\ -1.148\cdot 10^{-10}Re^2 + 2.675\cdot 10^{-6}Re + \\ +1.049; \quad Re = 5\cdot 10^3 \div 1.5\cdot 10^4; \\ -3.567\cdot 10^{-8}Re + \\ +1.063; \quad Re = 1.5\cdot 10^4 \div 1.5\cdot 10^5; \end{cases} \\ Re = \dfrac{4q_{v.ref}\rho}{\pi\mu D}. \end{cases} \tag{8}$$

The values of flow rate calculated on the basis of the mathematical model (8) were compared to the experimental values of flow rate measured by means of USM GUVR-011A2.2/VS. To calculate the relative deviation between the calculated and the measured values of flow rate (δ_M) the values of flow rate were reduced to standard conditions by applying a similar formula to formula (6).

The relative deviation was calculated according to the following formula

$$\delta_M = \frac{q_{s.CFD} - q_{s.GUVR}}{q_{s.GUVR}} \cdot 100 \qquad (9)$$

The curves of the relative deviation δ_M versus flow rate are presented in Figs. 9 and 10.

As we can see from Figs. 9 and 10 the simulation results are close to the experimental values in the range of flow rate from $0.05q_{v.max}$ to $q_{v.max}$. For USM installed downstream of 90° bend the maximum value of δ_M is 0.86 % in the specified range of flow rate. And for USM installed downstream of two 90° bends in perpendicular planes ($l \leq 5D$) the maximum value of δ_M is 1.04 %. By means of these results the adequacy of the proposed technique is proved and the possibility of application of this technique for studying the effect of flow disturbances on the error of flow rate measurement by USMs is confirmed.

Definition of minimum pipe straight lengths

The developed technique was applied for studying the additional errors of USMs caused by flow disturbances downstream of typical fittings with relation to the distance between the fitting and the USM (l_{fit}). The following types of USM were taken to consideration:

1. USM1 – double-path chordal USMs with the angle of acoustic paths j = 45°… 67°; calculation of the position coordinates and the weighting factors of the acoustic paths was carried out according to the improved method.
2. USM2 – double-path chordal USM GUVR-011A2.2/VS (G400, Dn100) with the angle of acoustic paths j = 67°; the position coordinates and the weighting factors of the acoustic paths were set according to [13].
3. USM3 – double-path chordal USM with the angle of acoustic paths j = 67°; calculation of the weighting factors of the acoustic paths was carried out according to the improved method.

The following fluid parameters were taken for simulation:

- type of fluid – air;
- fluid pressure and temperature – p = 400 kPa, T = 293.15 K (20 °C);
- reference values of flow rate: $q_v = q_{v.max} \times (0.025; 0.05; 0.1; 0.25; 0.5; 0.75; 1)$, $q_{v.max} = 650$ m^3/h.

The additional error of flow rate measurement caused by flow disturbance was calculated according to the following formula

$$\delta_A = \frac{q_s - q_{s.ref}}{q_{s.ref}} \cdot 100 \qquad (10)$$

The results of δ_A calculation for various flow rates are presented in Fig. 11.

The minimum pipe straight lengths l_{min} between a fitting and USM (see Table 1) were defined on the basis of the simulation results with taking into account the following criteria:

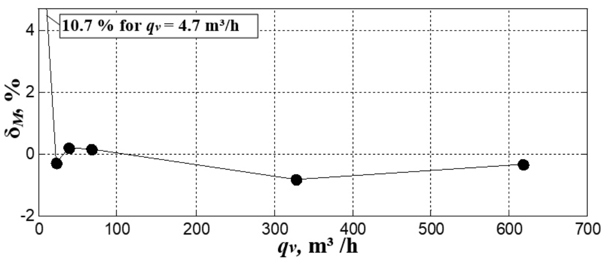

Figure 9. Relative deviation δ_M versus flow rate for USM installed downstream of 90° bend

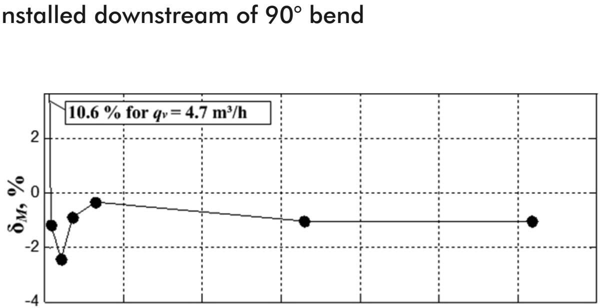

Figure 10. Relative deviation δ_M versus flow rate for USM installed downstream of two 90° bends in perpendicular planes (l≤5D)

Table 1. Minimum pipe straight length for USM installed downstream of the fitting

No	Type of fitting	l_{min}, ≥ l/D		
		USM1	USM2	USM3
1	Single 90° bend	50	30	30
2	Two 90° bends in perpendicular planes ($l \leq 5$D)	40	40	30
3	Gagged tee with change of flow direction	50	50	40
4	Two 90° bends in the same plane: U-configuration ($l \leq 10$D)	50	50	40
5	Two 90° bends in the same plane: S-configuration ($l \leq 10$D)	60	60	50
6	Expander (80/100)D	20	20	20
7	Reducer (130/100)D	40	20	20

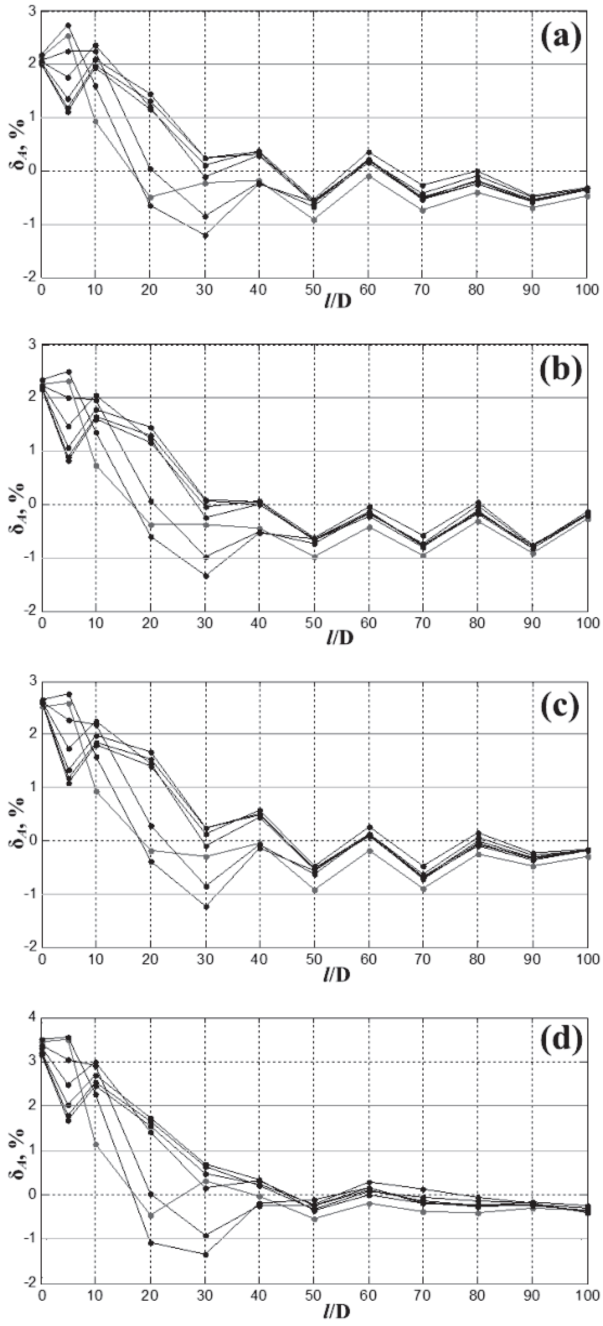

Figure 11. Relative error δ_A versus relative pipe straight length for USM installed downstream of two 90° bends in perpendicular planes ($l \le 5D$): a – $\varphi=45°$; b – $\varphi=55°$; c – $\varphi=55°$; d – GUVR $\varphi=67°$

– l_{min} is equal to the minimum length at which the value of δ_A error remains within the limits of the basic relative error of flow rate measurement declared by the manufacturer of USM;

- l_{min} is equal to the length at which prolonging the length by 10D would not lead to change of δ_A error by more than 0.3 %.

The greater value of l_{min} was accepted in each case when making the Table 1 based on the two criteria mentioned above.

As we can see from Fig.11 the minimum pipe straight length l_{min} defined on the basis of the two criteria for USM installed downstream of two 90° bends in perpendicular planes ($l \le 5D$) is 33D. The additional error of flow rate measurement δ_A is within the limits ±1 % for the double-path chordal USMs under consideration in the range of flow rate measurement from $q_{v.min}$ to $q_{v.max}$.

Based on the results presented in Table 1 we can say that the shortest pipe straight lengths are needed for USMs installed downstream of an expander. And the longest pipe straight lengths are needed for USMs installed downstream of two 90° bends in the same plane: S-configuration ($l \le 10D$).

Conclusions

Thus, the method for defining the position coordinates and the weighting factors of the acoustic paths was improved which provided reduction of the error of flow rate measurement.

An improved methodology was proposed in order to build a mathematical model of an USM of any construction.

The technique for studying the error of flow rate measurement was developed and verified on the basis of the results of experimental study of flow rate measurement error for an acting USM GUVR-011A2.2/VS in a test rig.

The recommendations to the minimum pipe straight lengths for the double-path chordal USMs without a flow conditioner were defined.

Bibliography

[1] Measurement of fluid flow in closed conduits – Ultrasonic meters for gas. Part 1: Meters for custody transfer and allocation measurement: ISO 17089-1 : 2010. – [First edition 2010-11-15]. – Geneva (Switzerland) : International Organization for Standardization (ISO), 2010. – 100 pages. (International standard).

[2] Ruppel, C., and Peters, F. (2004) Effects of upstream installations on the reading of an ultrasonic flowmeter. *Flow* Measurement and Instrumentation, 15, 167–177. doi:10.1016/j.flowmeasinst.2003.12.004.

[3] Merzkirch, W., Gersten, K., Hans, V., Lavante, E.V., Peters, F., & Ram V.V. (2005). Fluid mechanics of flow metering. New York, USA : Springer.

[4] Voser, A. (1999). Analysis and error optimization of multipath strength acoustic flow measurement in water turbines. Unpublished master's doctoral dissertation, Swiss Federal Institute of Technology Zurich, Zurich, Switzerland.

[5] Hilgenstock, A., and Ernst, R. (1996) Analysis of installation effects by means of computational fluid dynamics – CFD vs experiments? *Flow* Meas. Instrum, 7 (¾), 161–171. doi:10.1016/S0955-5986(97)88066-1.

[6] In-service performance of ultrasonic flowmeters – Application and validation of CFD modelling methods : technical report no. 2002/72 / edit by N. A. Barton. – Glasgow: National Engineering Laboratory, 2002. – 43 pages.

[7] Staubli, T., Luscher, B., Senn F., and Widmen, M. (2007) CFD optimized acoustic flow measurement and laboratory verifica-

tion. *Proceedings of the international conference HYDRO*, Granada, 14–18 October 2007, 7 pages.

[8] Press, W. H., Teukolsky S. A., Vetterling W. T., & Flannery B. P. (1995). Numerical Recipes in C (2nd ed.). Cambridge, England: Cambridge University Press.

[9] The Measurement, instrumentation, and sensors: handbook / edit by J. G. Webster. – Boca Raton (USA) : CRC Press, 1999. – 2630 pages.

[10] Roman V., Matiko F. Definition of weighting factors of acoustic paths of ultrasonic flow meters // Metrology and instrumentation . – 2014. – No 3(47). – p. 11-20 (in Ukrainian).

[11] Moore, P. I., Brown, G. J., & Simpson, B. P. (2000). Ultrasonic transit-time flowmeters modeled with theoretical velocity profiles: methodology. Meas. Sci. Technol, 11, 1802-1811.

[12] Pistun Y., Matiko F., Roman V., Stetsenko A. Investigation of the error of ultrasonic flow meters in disturbed flow based on CFD simulation // Metrology and instrumentation . – 2014. – No 4. – p. 13-23 (in Ukrainian).

[13] Ultrasonic Gas Meters GUVR-011: Instruction Manual 636128.310-1 RE / “Takhion” Private Company. – Kharkiv, Ukraine, 2013. – 58 p. (in Russian).

Authors: Cand. of Techn. Sci. (Ph.D. Eng.) Vitaliy ROMAN *- Lecturer of Department of Automation of Heat and Chemical Processes at Lviv Polytechnic National University, Ukraine. He obtained the degree of Candidate of Technical Sciences in Instruments and Methods of Measurement of Mechanical Quantities in 2015. His research interests are measurement of flowrate and volume of natural gas, CFD simulation of fluid flows, building algorithms and programs for flowmeters.*

Dr. of Techn. Sci. Fedir MATIKO *- Associate Professor of Department of Automation of Heat and Chemical Processes at Lviv Polytechnic National University, Ukraine. He obtained the degree of Doctor of Technical Sciences in Instruments and Methods of Measurement of Mechanical Quantities in 2015. His research interests are measurement of flowrate and volume of fluid energy carriers, development of normative documents for fluid flow rate and volume measurement, definition of natural gas balances and unbalances in gas transportation and gas distributing networks.*

Cand. of Techn. Sci. (Ph.D. Eng.) Roman FEDORYSHYN *- Associate Professor of Department of Automation of Heat and Chemical Processes at Lviv Polytechnic National University, Ukraine. He obtained the degree of Candidate of Technical Sciences in Instruments and Methods of Measurement of Mechanical Quantities in 2007. His research interests are measurement of flowrate and volume of natural gas, mathematical modeling of fluid flows, calculation of heat exchange processes in flow metering systems.*