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THE POSSIBILITY OF THE ANALITICAL SETTING OF ULTRASONIC FLOW-METER CHARACTERISTIC IN THE STANDARD CONDITIONS OF SETTLEMENT

Summary. In the paper a short review of the ultrasonic flowmeter and its working principle are introduced. In the standard conditions of settlements, which are described it is possible to calibrate an ultrasonic flowmeter without a calibration station. The mathematical model for laminar and turbulent flow connects the flowmeter output signal with volumetric flow. The total error is theoretically derived on the ground of an analysis of 14 error sources and experimentally verified in the calibration station for two flowmeters: UF 311 and UMP-10.

1. Introduction

Lately ultrasonic flowmeters have found greater and greater use for measurements of flow rate. They are used for measurement of flow rate both in pipes and open channels. These flowmeters have many advantages in comparison with other flowmeters [6, 13]. There are many possibilities of using an ultrasound for measuring of flow rate: 1) measurement based on the apparent differences of the velocity of sound in still water and moving water, 2) beam deflection effect, 3) Doppler effect, 4) Karman effect, 5) noise effect, 6) crossed-beam correlation technique. In ultrasonic flowmeters which are put on the market the first possibility is the most common.
The information about the flow rate can be included in: 1) time difference, 2) frequency difference, 3) phase difference and two first methods are most frequently used. There are two technical solutions: ultrasonic flowmeters with transducers inserted in the pipe wall and with clamp-on transducers [2, 4, 7, 8, 10]. In this two solutions the output signal depends on parameters which are connected with assembling of ultrasonic transducers (place of assembling, parameters of fluid, method of assembling). In certain conditions it is possible to constitute the ultrasonic characteristic. This analytical calibration is cheaper and easier than experimental one in a calibration station or in a spot of work. The calibration using mathematical model can be done in certain conditions, it means in standard conditions of settlement.

2. Standard conditions of settlement

Standard conditions of settlement are those, which must be kept during assembling of a measuring instrument in the purpose of correct use and they take into consideration instrument structure and destination. This conditions for one-path ultrasonic flowmeter are following: 1) the pipe has circular section, 2) axial-symmetrical velocity distribution, 3) single-phase fluid, 4) proper transducer assembling on the pipe or in the pipe wall. These demands are never performed perfectly, for example axial-symmetrical velocity distribution will be in places with straight pipe segments in upstream and downstream direction, but in literature there are no rules like for orifice meters. E. Hoene sugested [5] that for ultrasonic flowmeters the length of the straight pipe segments should be similar like for orifice and Ventury tubes.
The single-phase fluid for liquid means that it is free of suspended solids, sediments and gas bubbles. In this paper proper transducers assembling means diametral installing of one pair transducers. It is possible that one-path measuring sensor has two channels (four transducers). In purpose to achieve greater accuracy multi-path measuring sensors are constructed and dimensions must be very well known.

3. Mathematical model of ultrasonic flowmeter

The functional diagram of the ultrasonic flowmeter is shown in figure 1. The blocks 1 and 2 represent the source of the measuring quantity, 3 and 4 - the measuring sensor.

The velocity v_l is given by:

$$v_l = \frac{1}{l}\int_0^l v(l)dl, \tag{1}$$

where: l - distance between transducers.
Measuring quantity $\dot{V}$ is given by the formula:

$$\dot{V} = \iint_S v dS = \frac{1}{S} v_S = \frac{4}{\pi D^2} v_S, \tag{2}$$

where:

S - the pipe area,

D - the inside pipe diameter,

v_S - the mean velocity in the pipe section.

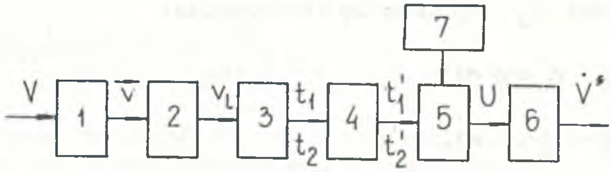

Fig. 1. The functional diagram of the ultrasonic flowmeter

1 - the transmission of measuring quantity $\dot{V}$ to vector field $\vec{v}$ in pipe section where the transducers are assembled, 2 - receiving the mean velocity v_l between the transducers, 3 - transmission v_l to two travel times of an ultrasonic beam: t_1 - in the downstream direction and t_2 - in the upstream direction, 4 - the addition of delays in transducers and in a pipe wall (for the clamp-on transducers), 5 - the measuring converter, 6 - the secondary device (the meter or the recorder graduated in flow units), 7 - the feeder, U - the output signal from 5

Rys. 1. Schemat funkcjonalny przepływomierza ultradźwiękowego

1 - przetwarzanie mierzonej wielkości $\dot{V}$ w wektorowe pole prędkości $\vec{v}$ w odcinku rurociągu, w którym zainstalowane są przetworniki, 2 - otrzymywanie prędkości średniej v_l między przetwornikami, 3 - przetwarzanie v_l na dwa czasy przebiegu fali ultradźwiękowej: t_1 - w kierunku z przepływem, t_2 - w kierunku pod prąd, 4 - dodanie się opóźnień w przetwornikach i w ścianie rurociągu (w przypadku przetworników nakładanych), 5 - przetwornik pomiarowy, 6 - przyrząd wtórny (miernik lub rejestrator wyskalowany w jednostkach przepływu), 7 - zasilanie, U - sygnał wyjściowy z 5

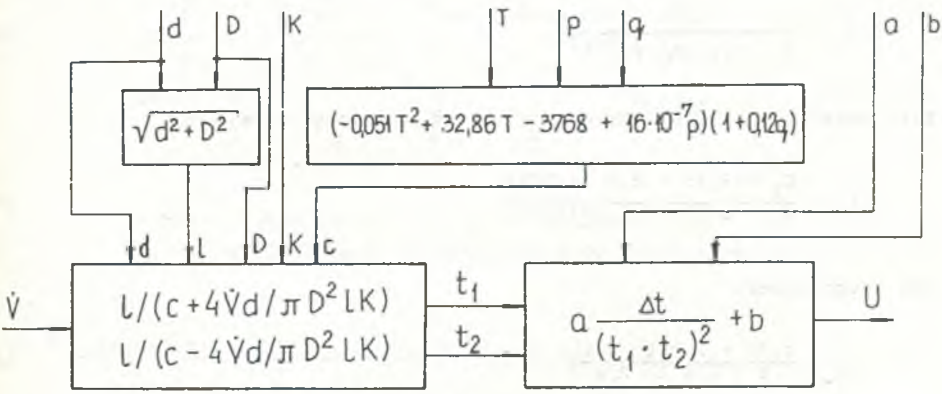

Fig. 2. The structural diagram of ultrasonic flowmeter with correction of c

d - the projection of the distance between transducers on the pipe axis, a - the sensitivity of the measuring converter, b - the output of the measuring converter for $t_2 - t_1 = 0$

Rys. 2. Schemat strukturalny przepływomierza ultradźwiękowego z korekcją c

d - rzut odległości między przetwornikami na oś rurociągu, a - czułość przetwornika pomiarowego, b - wyjście przetwornika pomiarowego dla $t_2 - t_1 = 0$

The velocity distribution is characterised by the factor K:

$$K = v_s/v_l. \tag{3}$$

The times t_1 and t_2 are given by the formulas:

$$t_1 = l/(c + v_1 \cos\alpha), \tag{4}$$

$$t_2 = l/(c - v_1 \cos\alpha), \tag{5}$$

where:

c - the sound velocity,

α - the angle between the path 1 and the axis of the pipe.

The sound velocity depends on temperature $T[K]$, pressure $p[Pa]$ and concentration of solids q [kg/kg] and for water the function is given in figure 2. In this figure it is showed the structural diagram of ultrasonic flowmeter with the correction of c. The factor K depends on a kind of flow. For laminar flow $K = 0,75$, for turbulent flow it depends on Reynold's number and on the relative roughness of the pipe k/R, where k is the absolute roughness, R - the pipe inside diameter.

For each region of turbulent flow K may be expressed by the following formulas:

for hydraulic smooth pipe:

$$K_1 = \frac{1}{1 + 1,25(\lambda_1/8)^{1/2}}, \tag{6}$$

for transition region between the smooth and rough pipes:

$$K_2 = \frac{C_2 - 3,75 + 2,5\ \ln(R/k)}{C_2 - 2,5 + 2,5\ \ln(R/k)}, \tag{7}$$

for rough pipes:

$$K_3 = \frac{4,75 + 2,5\ \ln R/k}{6 + 2,5\ \ln R/k}, \tag{8}$$

where:

λ_1 - the hydraulic resistance,

C_2 - the constant calculated on the base of experimental results received by Nikuradse [9], $R = D/2$.

The value of K have been calculated on the base of formulas (6), (7), (8) [11] and are given in the figure 3.

K for a critical flow must be calculated on the base of experimental data. The mathematical model of an ultrasonic flowmeter can be written from fig.2 and formulas (6), (7), (8).

For example for rough pipes:

$$U = \frac{2\ d\ a\left[6 + 2{,}5\ \ln(R/k)\right]}{\pi D^2 l^2\left[4{,}75 + 2{,}5\ \ln(R/k)\right]}\ \dot{V} + b, \tag{9}$$

The measured quantity (volumetric flow) is reconstructed with antifunction to the formula (9) as the visual signal $\dot{V}$ (fig. 1).

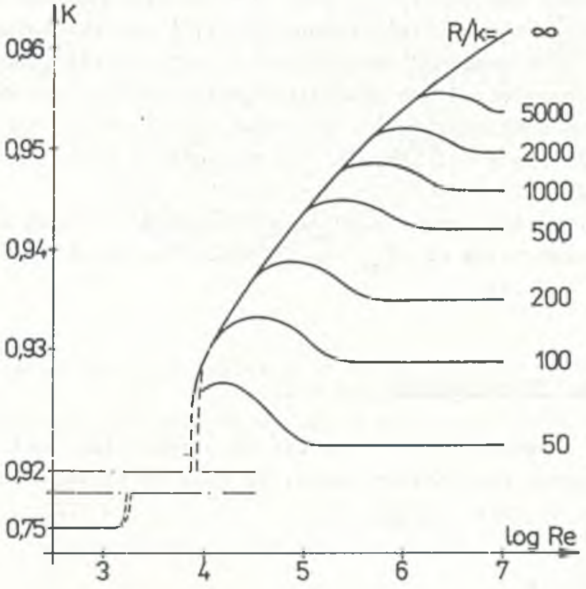

Fig. 3. The factor K for a turbulent flow
Rys. 3. Współczynnik K dla przepływu burzliwego

4. The error in the standard conditions of settlements

The total error has many sources [3] and every partial error has a random character, so error summation will be according to a geometrical rule [1]. The total error can be expressed by the formula:

$$\delta = (\delta^2_{ms} + \delta^2_{ac} + \delta^2_{mc} + \delta^2_{sd})^{1/2}, \tag{10}$$

where:

δ_{ms} - the measuring sensor error,
δ_{ac} - the error of the analitical calibration procedure,

δ_{mc} - the measuring converter error,
δ_{sd} - the secondary device error.

The measuring sensor error consists of: the nonlinear error, the error caused by a drift of the ultrasonic beam, the error caused by conditions of transducers assembling (the noncircular section of the pipe, the differences in the pipe diameters, the uncertainty of roughness setting), the error of transducers assembling, the additional errors (caused by a variation of temperature, pressure and density of fluid). The errors caused by transducers assembling have been analised in details [12] and the value has been found to be 0,62%. The error of the analytical calibration procedure is equal to 0,79%. The error of the measuring converter has been determined experimentally (the nonlinear error, the unstability error, the influence of temperature and supply voltage) and for the place, in which flowmeter is used is given as 0,32%.

δ_{sd} is equal 0,075%. All errors have been estimated for 0,95 confidence level. The calculated value of δ_{ms} is 0,98%. The total error calculated from formula (10) is 1,3%.

5. Experimental investigations

The ultrasonic flowmeter is used in concrete conditions and very often the flow changes about the certain value. In this situation simpler formula is used then given by (9):

$$U = \frac{2\,d\,a}{\pi D^2 l^2 K}\dot{V} + b, \tag{11}$$

where value of the factor K is for nominal or maximum expected flow. The checked flowmeters are as follows: UF 311 (produced by French firm Ultraflux [8] and UMP-10 produced by Polish firm TECHPAN [10]). Both flowmeters work basing on time defference principle. The measuring converter of UF 311 is analog, of UMP-10 is digital. Both firms offer 1% error.

The experimental checking has been done in the calibration station in Chorzów, which has got two volumetric tanks of 19,133 $[m^3]$ and 38 $[m^3]$ arranged in rows. The transducers of the flowmeters have been installed in the wall of the pipe of inside diameter 0,39 $[m]$. The stand was supplied from the tank with an air cushion. A straight pipe segment in up-stream direction is 9D and in down-stream direction 2,5 D. The knees are before and behind these segments. The error of the flow in pipe has been calculated and it has not been higher than 0,3%.

On the base of the roughness k and maximum Reynolds number the factor K has been taken from fig. 3 (0,9475). The velocity distribution has been checked in consideration of short straight segments of the pipe with help

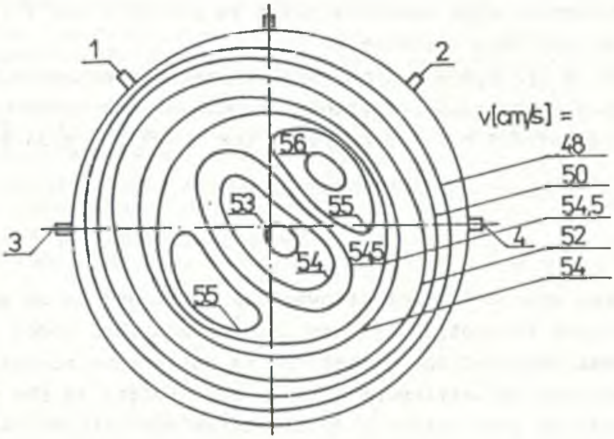

Fig. 4. The lines of equal velocity of water in the pipe of diameter 0,39 [m]

Rys. 4. Izotachy dla przepływu wody w rurze o średnicy 0,39 [m]

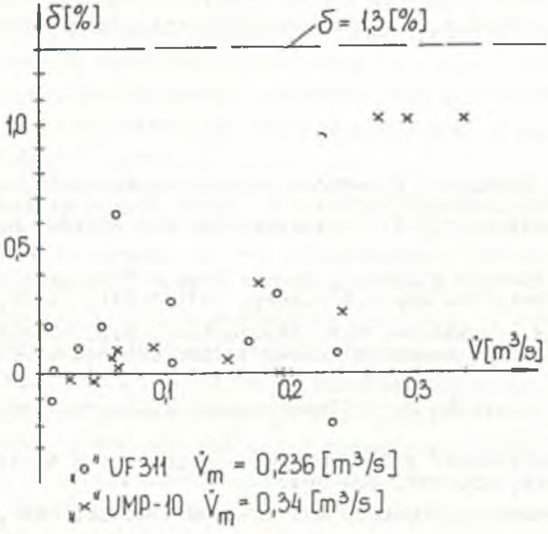

Fig. 5. The relative errors for the checked ultrasonic flowmeters UF 311 and UMP-10

Rys. 5. Błędy względne dla badanych przepływomierzy ultradźwiękowych UF 311 i UMP-10 of the firm Bestobell Meter Flow Limited (England, 1980) turbine insertion flowmeter in points 1 and 2 fig. 4.

In the figure 4 the lines of equal velocity are drown. The transducers of the ultrasonic flowmeter have been installed in points 3 and 4 (fig. 4) and the factor K has been calculated.

The real value of K is 0,977 and this value has been taken to the formula (11). In the figure 5 the relative errors are drown with reference to the measuring range for UF 311 - 0,236 $[m^3/s]$, for UMP-10 - 0,34 $[m^3/s]$.

6. Summary

The experimental errors for both flowmeters are found to be placed in the limits calculated theoretically from the mathematical model of the flowmeter when the real value of the factor K is taken into account. One of the standard condition of settlement has not been fulfil in the place of transducers installing (the velocity distribution has not been axial-symmetrical).

The distortion of the velocity distribution has been caused by a short straight pipe section in the upstream and the downstream directions and in every such situation the velocity distribution must be checked. The flowmeter errors (shown in the fig. 5) have sistematic component (the sensitivity error).

The reason of this component can be uncertainty of setting K or the influence of different sources of errors which do not reduce each other.

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MOŻLIWOŚĆ ANALITYCZNEGO WYZNACZANIA CHARAKTERYSTYKI PRZEPŁYWOMIERZA ULTRADŹWIĘKOWEGO W NORMALNYCH WARUNKACH ZABUDOWY

S t r e s z c z e n i e

Podstawowymi zaletami przepływomierza ultradźwiękowego są możliwość instalowania bez konieczności przerywania przepływu oraz możliwość analitycznego wzorcowania bez konieczności używania stacji wzorcowania. Możliwość ta istnieje dla normalnych warunków zabudowy (kołowy przekrój rurociągu, znana chropowatość, osiowo-symetryczny rozkład prędkości, ciecz jednofazowa, prawidłowo zainstalowane głowice).

Dla przepływu burzliwego wyznaczono stosunek v_S (średnia prędkość w przekroju) do v_1 (średnia prędkość w drodze fali ultradźwiękowej) dla rury hydraulicznie gładkiej oraz dla rur chropowatych. Został wyprowadzony model czujnika, tzn. zależność Δt od strumienia objętości $\dot{V}$. Model ten jest nieliniowy i zawiera średnicę wewnętrzną rurociągu D, odległość między przetwornikami l oraz warunki pomiaru: lepkość cieczy ν, temperaturę T i ciśnienie p. Wielkość mierzona, tzn. strumień objętości $\dot{V}$ jest odtwarzana za pomocą funkcji przeciwnej do modelu czujnika.

Dla konkretnego przykładu obliczono teoretycznie błąd całkowity na podstawie analizy 14 źródeł błędów: błąd nieliniowości, błędy związane z kształtem rurociągu, błędy powstające przy instalowaniu przetworników,... W konkretnym przypadku zastosowania przepływomierza ultradźwiękowego (D = 0,4 m) obliczony dla poziomu ufności 95% błąd wynosił 1,3%. Wynik ten został zweryfikowany doświadczalnie w stacji wzorcowania dla dwóch przepływomierzy: UF 311 (produkcji francuskiej firmy Ultraflux) i UMP-10 (produkcji polskiej firmy TECHPAN) zainstalowanych w rurociągu o średnicy 0,4 m. Błąd pierwsze-

go przepływomierza dla $Re = 10^3 - 10^6$ nie był większy niż 1,1%, dla drugiego przepływomierza mniejszy niż 1,3%. Doświadczalne badania potwierdziły więc możliwość analitycznego wyznaczania charakterystyki przepływomierza. Warunkiem otrzymania satysfakcjonującego błędu jest spełnienie normalnych warunków zabudowy.

ВОЗМОЖНОСТИ АНАЛИТИЧЕСКОГО ОПРЕДЕЛЕНИЯ ХАРАКТЕРИСТИКИ УЛЬТРАЗВУКОВОГО РАСХОДОМЕРА В НОРМАЛЬНЫХ УСЛОВИЯХ ЕГО ЗАСТРОЙКИ

Р е з ю м е

В работе дано краткое ревью ультразвуковых расходомеров и показан принцип их работы. В стандартных условиях показана возможность аналитической калибровки без необходимости использования эталонной станции. Математическая модель для ламинарного и турбулентного потока включает выходной сигнал расходомера и параметры потока. Дан теоретический расчёт суммарной ошибки, расчитанной на основе 14 составных ошибок и впоследствии верифицирована она на калибровочной станции для двух расходомеров: UF 311 и UMP-10.