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Merilna negotovost pri merjenju tokov fluidov na podlagi dušilnih metod

Uncertainty of Measurement in Fluid Flow Measurement on the Basis of Differential Pressure Methods

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Merjenje tokov enofaznih fluidov na podlagi dušilnih metod je najpogosteji način merjenja tokov v industriji. V fazi načrtovanja preizkusa nas zanima, ali bosta izbrana merilna metoda oziroma merilna oprema zadostila našim zahtevam glede merilne točnosti.

Raziskovali smo vplive na merilno negotovost pri merjenju tokov fluidov z ostrorobo merilno zaslонko in določili tokovne oziroma geometrijske oblike, pri katerih lahko pričakujemo zadovoljivo merilno točnost.

Measuring one-phase fluid flows on the basis of differential pressure methods is the most often used principle for measurement of flows in industry. In the planning phase of an experiment one needs to know whether or not the chosen measuring method or measuring equipment will meet requirements for measurement uncertainty.

The influences on measurement uncertainty in measuring fluid flows with square-edged orifice plate were investigated and the conditions of flow and geometry where we expect to achieve the satisfactory accuracy of measurement were determined.

0 UVOD

Za merjenje tokov fluidov imamo na voljo veliko število merilnih metod, ki slonijo na različnih fizikalnih načelih. Po nekaterih ocenah je prek 50 odstotkov meritev izvedenih na podlagi dušilnih metod [1]. Tok fluida v cevi dušimo z lokalnimi ovirami, ki povzročajo značilno porazdelitev statičnega tlaka v okolini ovire. Razlika statičnih tlakov pred oviro in za njo je pri ustavljenem toku temelj za napoved vrednosti toka fluida. Poznamo veliko število različnih dušilnih elementov, standardiziranih (ISO 5167) in nestandardiziranih. V industrijskih meritvah tokov je najpogosteje zastopana merilna zaslonka, samo v ZDA naj bi bilo vgrajenih čez milijon takih zaznaval [2].

Pri vsaki meritvi je ena največjih težav zagotoviti želeno merilno točnost oziroma določiti merilno negotovost. V tem prispevku smo se omejili na raziskovanje merilne negotovosti pri merjenju tokov fluidov z ostrorobo merilno zaslonko. Analiza merilne negotovosti je zlasti koristna v fazi načrtovanja preizkusa, ko izbiramo merilno opremo glede na določene dejanske razmere.

0 INTRODUCTION

A large number of measurement methods for fluid flow measurement based on different physical principles is available. According to some estimations, more than 50 percent of measurements are performed on the basis of differential pressure methods [1]. The fluid flow in a pipe is disturbed by using local barriers, which cause a typical distribution of static pressure in the barrier neighbourhood. The difference between static pressures upstream and downstream from the barrier is in steady flow the basis for the prediction of fluid flow rate. Many different disturbance elements are available, both standardized (ISO 5167) and nonstandardized. In industrial fluid flow measurement, an orifice plate is most frequently used; over one million such sensors [2] are believed to be installed.

In any measurement, one of the greatest difficulties is to ensure the desired accuracy or, respectively, to determine the uncertainty. In our paper we have decided to focus on the research of measurement uncertainty in measuring fluid flow with a square-edged orifice plate. The measurement uncertainty analysis is particularly useful in the planning phase of an experiment, when we select the measuring equipment according to certain real conditions.

1 MERILNA TOČNOST IN MERILNA NEGOTOVOST

V eksperimentalnem raziskovanju velja glavno načelo — nobena meritev ni brez pogreška [3]. Pogrešek meritve nastane zaradi nepopolnosti merilnega zaznavala, merilnega postopka, objekta merjenja, vplivov okolice in eksperimentatorja. Celotni merilni pogrešek je sestavljen iz naključnega in sistemskoga pogreška. Za ocenjevanje eksperimentalnega pogreška se uporablja pojma merilna točnost in merilna negotovost.

Merilna točnost pomeni skladnost merilnega rezultata s pravo (dogovorno) vrednostjo merjene veličine [4]. To je številčna vrednost, s katero proizvajalec zagotavlja natančnost meritve z določenim merilnikom. Bolj teoretičen pojem je merilna negotovost W , ki je definirana kot ocena, s katero se označuje območje vrednosti, v katerem leži prava vrednost merjene veličine.

Merilni izid neke meritve je aritmetično povprečje x_s večjega števila odbirkov (popravljeno za znane sistemski pogreški), povezana z določenim območjem zaupanja, v katerem domnevno leži prava vrednost merjene veličine. Območje zaupanja običajno podamo s 95-odstotno verjetnostjo. Prava vrednost merjene veličine x_p tako leži s 95-odstotno verjetnostjo v območju:

$$(x_s - W \leq x_p \leq x_s + W) \quad (1)$$

Posebej zanimivo je raziskovanje merilne negotovosti posrednih meritov, ko ne moremo meriti želene fizikalne veličine, lahko pa jo izračunamo iz nekaterih drugih merljivih ali kako drugače dočljivih veličin. Merjenje tokov fluidov po dušilnih metodah sodi med posredne meritve.

Za določanje merilne negotovosti posredno dočljive veličine se v praksi največ uporablja kvadratični zakon o razširjanju pogreškov ali statistična meja pogreškov, ki ga lahko izpeljemo na podlagi razvrstitev posredne funkcije $r = r(x_1, x_2, \dots, x_J)$ v Taylorjevo vrsto, pri kateri pa ohranimo samo linearne člene [5]. V fazi načrtovanja preizkusa, ko se odločamo o tem, ali bomo z določeno merilno metodo dobili zadovoljive rezultate glede merilne točnosti, je uporabna oblika kvadratnega zakona o razširjanju pogreškov takšna, kakršno predlagata Kline in McClintock [5]:

$$W_r^2 = \sum_{i=1}^J \Theta_i^2 W_i^2 \quad (2)$$

$$\Theta_i = \frac{\partial r}{\partial x_i} \quad (3)$$

1 ACCURACY AND UNCERTAINTY OF MEASUREMENT

In experimental research, the basic axiom stands — there is no measurement without error [3]. Error of measurement is a result of imperfection of the measuring sensor, measuring method, the object of measurement, environmental and experimenter influences. The total error of measurement is a compound of the precision error and bias error. To assess the error of measurement, the notions accuracy and uncertainty of measurement are used.

Accuracy of measurement means agreement of the measurement result with the true (absolute) value of the measured quantity [4]. This is the degree of accuracy (a numerical value) of measurement with a certain sensor guaranteed by the manufacturer. A more theoretical notion is uncertainty of measurement W , defined as an estimate of the range within which the true value of the measured quantity lies.

The result of a measurement is the arithmetic mean x_s of a large number of readings (corrected by the known bias errors), related to a certain confidence interval, in which hypothetically lies the true value of the measured quantity. We usually define the confidence interval with 95 percent of probability. So the true value of the measured quantity x_p lies with 95 percent probability in the interval:

The research of measurement uncertainty is especially interesting in indirect measurements, where we cannot measure the desired physical quantity, but we can calculate it from the value of another quantity, measured or obtained in a different way. The fluid flow measurements on the basis of different pressure methods belong to the group of indirect measurements.

The most useful method for determining the uncertainty of measurement of an indirectly definable quantity in practice is the square-law of error propagation or the statistical limit of errors, which we can deduce from Taylor's potential expansion series of indirect function $r = r(x_1, x_2, \dots, x_J)$ with only the linear terms retained [5]. In the planning phase of the experiment, when we decide whether we will obtain satisfactory results with a certain measuring method considering measurement accuracy, the useful form of the square-law of error propagation is the one proposed by Kline and McClintock [5]:

Spošni interval negotovosti W_1 neposredno določljive veličine x_1 je ocena, ki zajema sistemski in naključni del pogreška na naključen način, saj je v fazì načrtovanja preizkusa, ko še nismo izbrane posebne merilne opreme, sistemski pogrešek prav tako verjetno pozitiven kakor negativen. Ocene splošnih intervalov negotovosti W_1 pridobimo z uporabo trenutno najboljših dostopnih informacij (literatura, podatki proizvajalcev).

3 MERJENJE TOKOV FLUIDOV

Z OSTROROBO MERILNO ZASLONKO

Matematični model za izračun masnega toka fluida pri merjenju z ostromrobo merilno zaslonko dobimo po ohranitvenih zakonih: zakonu o ohranitvi mase in zakonu o ohranitvi energije. Ustrezni izraz je:

$$\dot{m} = \varepsilon \frac{C \pi d^2}{4} (2 \Delta p \rho_1)^{1/2} \quad (4)$$

kjer pomenijo: \dot{m} – masni tok fluida (kg/s), ε – ekspanzijsko število, C – pretočni koeficient, d – premer odprtine zaslonke (m), D – svetli premer cevovoda (m), β – geometrijsko razmerje premerov (d/D), Δp – razlika statičnih tlakov pred zaslonko in za njo (Pa), ρ_1 – gostota fluida pred zaslonko (kg/m^3).

Pretotčni koeficient C in ekspanzijsko število ε sta eksperimentalno dobljena podatka, preostali del enačbe (4) pa dobimo teoretično z uporabo kontinuitetne in Bernoullijeve enačbe. Shema obravnavanega merilnega sistema je predstavljena na sliki 1.

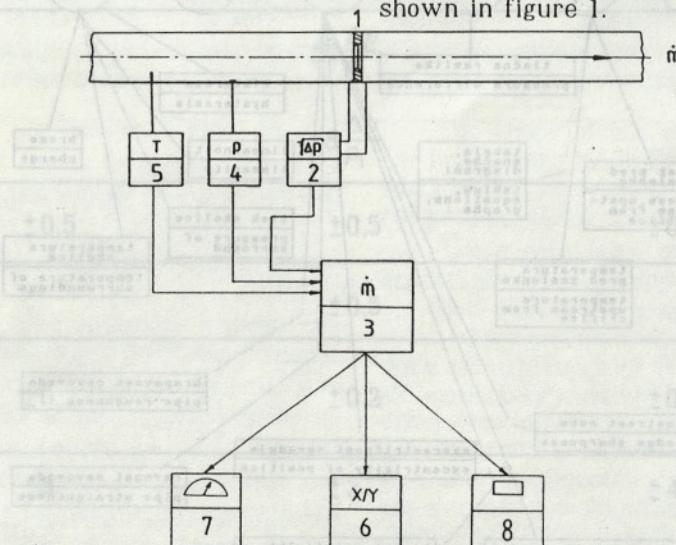
The general uncertainty interval W_1 of the directly definable quantity x_1 is only an estimate, which includes the bias and precision part of error at random because in the planning phase of an experiment, when we have not yet chosen the special measuring equipment, the bias error is with equal probability positive or negative. We obtain the estimates of general uncertainty intervals W_1 with the use of the best available information at the moment (literature, manufacturer's data).

3 FLUID FLOW MEASUREMENT WITH SQUARE-EDGED ORIFICE PLATE

The mathematical model for calculation of mass flow rate in measurement with square-edged orifice plate is developed on the basis of conservation laws – the law on conservation of mass/energy. The appropriate expression reads:

where: \dot{m} – mass flow rate (kg/s), ε – expansion factor, C – discharge coefficient, d – orifice hole diameter (m), D – inside diameter of pipe (m), β – geometric ratio ($\beta = d/D$), Δp – difference of static pressures up- and downstream from orifice (Pa), ρ_1 – fluid density upstream from orifice (kg/m^3).

The discharge coefficient C and the expansion factor ε are experimentally obtained, but we deduce the rest of equation (4) theoretically with the use of continuity and the Bernoulli equation. The scheme of the treated measuring system is shown in figure 1.



Sl. 1. Merilni sistem za merjenje toka fluida z ostromrobo merilno zaslonko

1 – merilna zaslonka, 2 – sekundarno zaznavalo za Δp , 3 – računska enota, 4 – zaznavalo za tlak, 5 – zaznavalo za temperaturo, 6, 7, 8 – prikaz rezultatov

Fig.1. The measurement system for measuring fluid flow with square-edged orifice plate

1 – orifice plate, 2 – secondary sensor for Δp , 3 – calculator, 4 – pressure sensor,

5 – temperature sensor, 6, 7, 8 – display of results

Vplivnih veličin na merilno negotovost masnega toka fluida je več, saj je vsaka od veličin na desni strani enačbe (4) lahko spet posredna funkcija nekih drugih veličin. Struktura vplivnih veličin na merilni pogrešek masnega toka fluida pri merjenju z ostrarobo merilno zaslonko je prikazana na sliki 2 [6], [7], [8]. Ugotovimo lahko, da je mogoče vplive na merilno negotovost obravnavati večstopenjsko. V našem prispevku smo se omejili na obravnavo primarnega in sekundarnega zaznavala (ostrorobe merilne zaslonke in tokovnega pretvornika tlache razlike). Želeli smo dobiti odgovora na dve vprašanji:

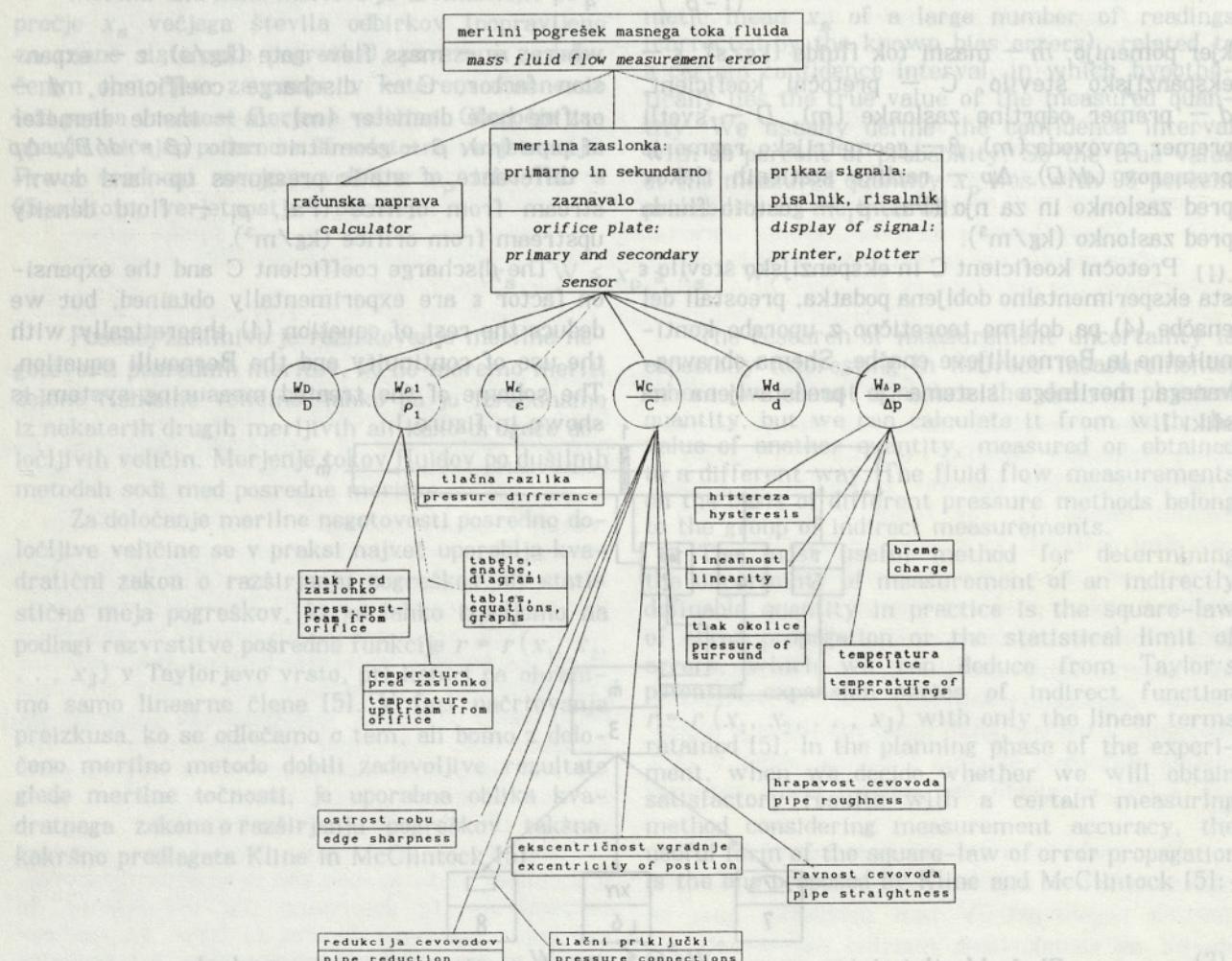
— Kako se spreminja merilna negotovost, če merimo tokove fluida, ki so različni od nominalnega (največjega) toka, za katerega je bila zaslonka dimenzionirana?

— Kako se spreminja merilna negotovost, če konstantni tok fluida v danem cevovodu merimo z zaslonkami različnih velikosti odprtin?

There are a number of influences on mass fluid flow measurement uncertainty, because each of the quantities on the right side of equation (4) can be an indirect function of some other quantities. The structure of factors influencing the mass fluid flow measurement error in measurement with a square-edged orifice plate is shown in figure 2 [6], [7], [8]. We can conclude that it is possible to deal with influences on measurement uncertainty at many levels. In our work we restricted ourselves to treating the primary and secondary sensor (the square-edged orifice plate and the current transmitter of pressure difference). We wished to get answers to two questions:

— How does measurement uncertainty change when we measure the rates of fluid flow which are different from nominal (maximum) flow rate for which the orifice plate was designed?

— How does measurement uncertainty change when we measure a constant fluid flow rate in a given pipe with orifice plates with different sizes of openings?



Sl. 2. Struktura vplivov na merilni pogrešek masnega toka pri merjenju z ostrarobo merilno zaslonko

Fig. 2. The structure of influences on mass flow measurement error in measuring with square-edged orifice plate

Z uporabo statistične meje pogreškov dobimo iz enačb (2) in (4) za merilno negotovost masnega toka fluida naslednji izraz:

$$\frac{W_m}{\dot{m}} = \left[\left(\frac{W_c}{C} \right)^2 + \left(\frac{W_\epsilon}{\epsilon} \right)^2 + \left(\frac{2\beta^4}{1-\beta^4} \right)^2 \left(\frac{W_D}{D} \right)^2 + \left(\frac{2}{1-\beta^4} \right)^2 \left(\frac{W_d}{d} \right)^2 + \frac{1}{4} \left(\frac{W_{\Delta p}}{\Delta p} \right)^2 + \frac{1}{4} \left(\frac{W_{\rho_1}}{\rho_1} \right)^2 \right]^{1/2} \quad (5).$$

V enačbi (5) smo predpostavili, da so veličine na desni strani enačbe (4) medsebojno neodvisne, kar dejansko ne drži [npr. $C = C(\beta, \dot{m})$; $\epsilon = \epsilon(\Delta p, \beta)$]. Standard ISO 5167 [6] pa za praktično uporabo dovoljuje predpostavko o neodvisnosti veličin C , ϵ , D , d , Δp in ρ_1 . Ocene splošnih območij negotovosti oziroma mej pogreškov za obravnavane neposredno določljive veličine smo dobili z uporabo ustreznih literatur [6], [9], [10], prikazane pa so v preglednici 1.

With the use of statistical limits of errors we get on the basis of equations (2) and (4) the following expression for mass flow rate measurement uncertainty:

$$\frac{W_m}{\dot{m}} = \left[\left(\frac{W_c}{C} \right)^2 + \left(\frac{W_\epsilon}{\epsilon} \right)^2 + \left(\frac{2\beta^4}{1-\beta^4} \right)^2 \left(\frac{W_D}{D} \right)^2 + \left(\frac{2}{1-\beta^4} \right)^2 \left(\frac{W_d}{d} \right)^2 + \frac{1}{4} \left(\frac{W_{\Delta p}}{\Delta p} \right)^2 + \frac{1}{4} \left(\frac{W_{\rho_1}}{\rho_1} \right)^2 \right]^{1/2} \quad (5).$$

In equation (5) we assume that the quantities on the right side of equation (4) are independent of each other, which in reality is not true [e.g. $C = C(\beta, \dot{m})$; $\epsilon = \epsilon(\Delta p, \beta)$]. But the ISO 5167 standard [6] allows the assumption of independence of quantities C , ϵ , D , d , Δp and ρ_1 for practical use. We used the estimates of general uncertainty intervals or estimates of error limits for treated direct definable quantities from references [6], [9], [10] and they are shown in table 1.

Preglednica 1: Meje pogreškov neposredno določljivih veličin

Table 1: The error limits of direct defineable quantities

Meje pogreškov (Error limits) (%)					
	spodnje lower	optimalne optimum	optimalne z neustrezno inst. optimum with inadequate inst.	zgornje upper	opombe comments
$\frac{W_c}{C}$	$\pm 0,6$	$\pm 0,6$	$\pm (0,6 + 0,5)$	$\pm (0,6 + 1)$	$\beta \leq 0,6$
$\frac{W_\epsilon}{\epsilon}$	$\pm \beta$	$\pm \beta$	$\pm (\beta + 0,5)$	$\pm (\beta + 1)$	$0,6 \leq \beta < 0,8$
$\frac{W_D}{D}$	$\pm 0,1$	$\pm 0,5$	$\pm 0,5$	$\pm 0,5$	
$\frac{W_d}{d}$			$\pm 0,5$		
$\frac{W_{\Delta p}}{\Delta p}^*$	$\pm 0,1$	$\pm 0,2$	$\pm 0,2$	$\pm 0,5$	* – v % polne skale
$\frac{W_{\rho_1}}{\rho_1}$	$\pm 0,05$	± 3	± 3	± 4	* – in % of full scale
	$\pm 0,03$	± 1	± 1	$\pm 1,5$	zrak in zem. plin air and natural gas
	$\pm 0,02$	$\pm 2,5$	$\pm 2,5$	± 3	voda water
					vodna para water steam

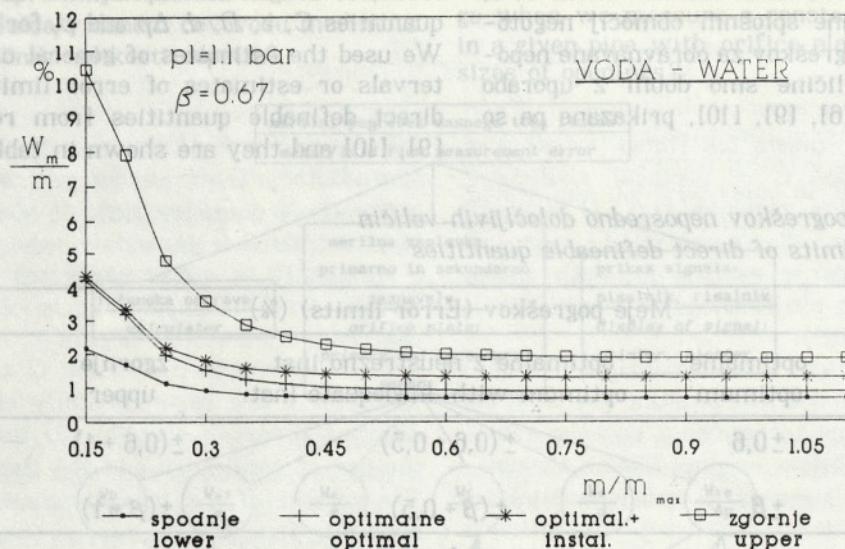
Indeks 1 se nanaša na lastnosti fluida pred zaslonko (ρ_1 , ρ_2)
Index 1 relates to properties of fluid upstream the orifice (ρ_1 , ρ_2)

Raziskovali smo merilno negotovost pri merjenju tokov fluidov štirih različnih medijev (vodna para, voda, komprimiran zrak in zemeljski plin) glede na dejanske razmere proizvodnje in porazdelitve energijskih sredstev v podjetju Sava, Kranj. Rezultati izračuna po enačbi (5) so prikazani za vodo in vodno paro na slikah 3 do 6. Na vsaki sliki so prikazane štiri različne krivulje, ki ponazarjajo naslednje meje pogreškov:

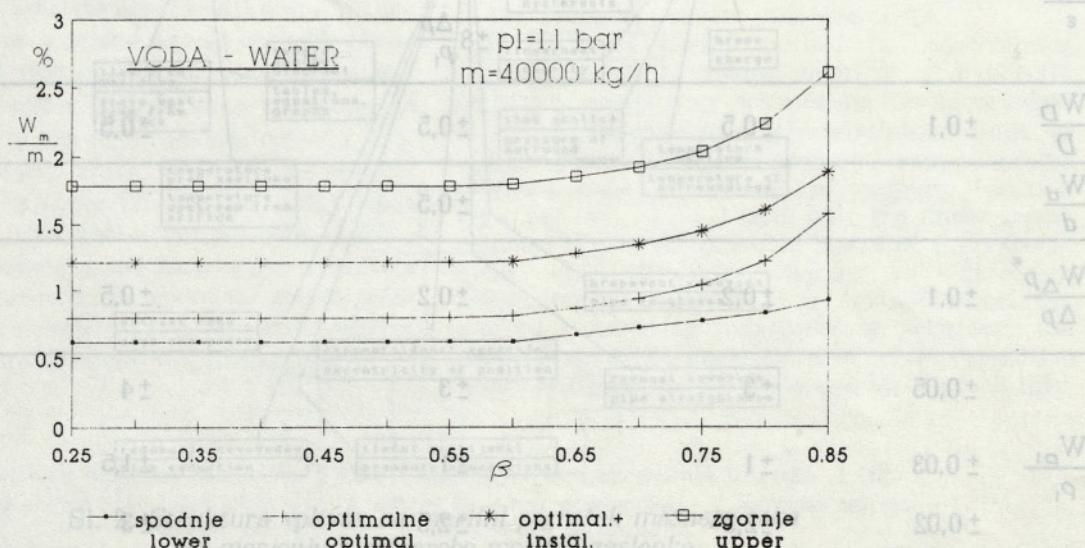
- spodnje (laboratorijske razmere),
- optimalne (realna pričakovanja ob zadostitvi pogojev o ustaljenosti toka in instalacijskih razmer),
- optimalne meje pogreškov z vplivom neustrezne instalacije (prekratek ravnji del cevovoda pred zaslonko) in
- zgornje meje pogreškov (najbolj neugodne razmere za meritve).

We investigated the measurement uncertainty by measuring fluid flow for four different media (water vapour, water, compressed air and natural gas) according to the concrete conditions of energy medium production and distribution at the Sava Kranj company. The results of calculation from equation (5) are represented graphically for water and water vapour in figures 3 to 6. In each figure, four different curves are presented, which illustrate the following limits of errors:

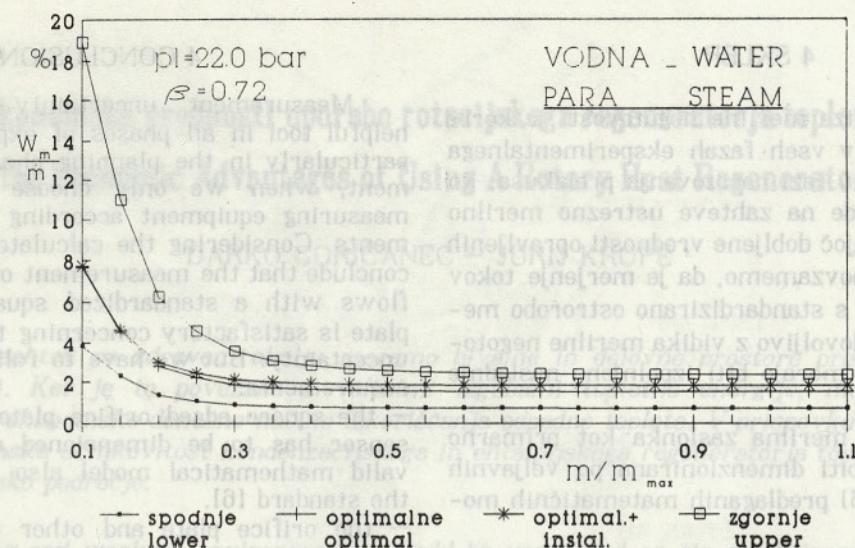
- lower (laboratory conditions),
- optimum (realistic expectations with stationary flow conditions and the installation conditions fulfilled),
- optimum limits of errors with the influence of inadequate installation (the straight part of the pipe upstream from the orifice too short) and,
- upper limits of errors (the most disadvantageous conditions for measurement).



Sl. 3. Meje pogreškov masnega toka vode v odvisnosti od razmerja masnih tokov
Fig. 3. The mass flow error limits for water in dependence on mass flow ratio

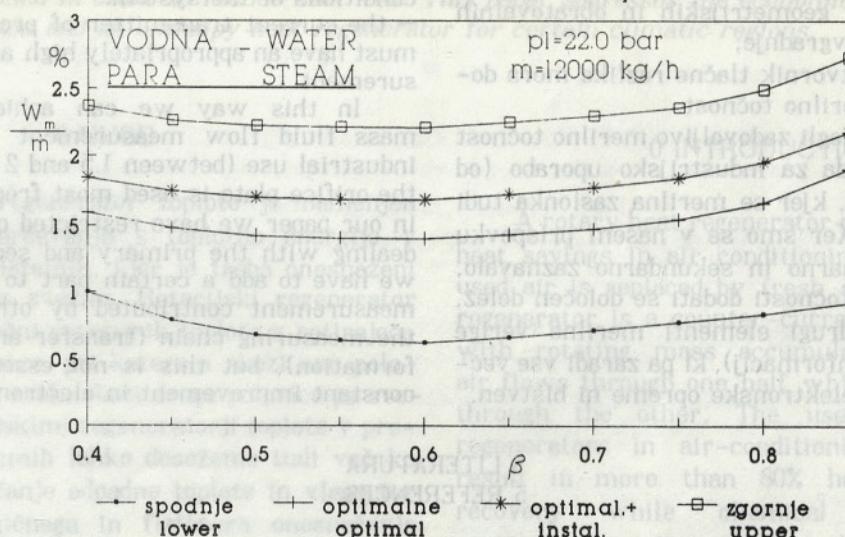


Sl. 4. Meje pogreškov masnega toka vode v odvisnosti od razmerja β
Fig. 4. The mass flow error limits for water in dependence on β ratio



Sl. 5. Meje pogreškov masnega toka vodne pare v odvisnosti od razmerja masnih tokov

Fig. 5. The mass flow error limits for water steam in dependence on mass flow ratio

Sl. 6. Meje pogreškov masnega toka vodne pare v odvisnosti od razmerja β Fig. 6. The mass flow error limits for water steam in dependence on β ratio

Oblika krivulj za komprimiran zrak in zemeljski plin je podobna kakor za vodno paro (vsi so stisljivi fluidi), zato teh grafov v tem prispevku ne podajamo.

Ugotovitve oziroma odgovori na zastavljeni vprašanji so naslednji:

Če želimo meriti tokove fluidov z relativno konstantno merilno negotovostjo po dovolj širokem območju tokov, je treba zanesljivo meriti predvsem tlačno razliko Δp , saj se sicer pri tokovih, ki so nekje pod 30 odstotki nominalnega toka, merilni pogrešek zelo poveča. V industriji ni redek primer, da se vrednosti tokov po cevovodih zelo spremenijo, zlasti glede na dinamiko odjema, ki je odvisna od značilnosti v tehnološkem procesu. Najbolj primerna velikost odprtine zaslonke pa je podana z geometrijskim razmerjem β med 0,5 in 0,7 za pline in pare ter pod 0,7 za kapljevine. V takih razmerah je merilna točnost najboljša [11].

The shape of the curves for compressed air and natural gas is similar to those of water vapour (they are all compressible fluids), therefore we do not present them specifically in our paper.

The conclusions, or answers to the questions asked, are as follows:

If we wish to measure fluid flow rates with relatively constant measurement uncertainty in a wide enough range of flow rates, we must above all accurately measure the pressure difference Δp , otherwise at flow rates below 30 percent of nominal flow rate, the error of measurement rises considerably. In industry, it is not rare that the flow rates in pipes considerably change, particularly according to the dynamics of take-off, which is determined by the features of the technological process. The most suitable size of opening in the orifice plate is given by the geometric β ratio ranging between 0.5 and 0.7 for gases and steams and below 0.7 for liquids. The accuracy of measurement is highest under these conditions [11].

4 SKLEP

Uporaba analize merilne negotovosti je korišten pripomoček v vseh fazah eksperimentalnega dela, zlasti pa še v fazi načrtovanja preizkusa, ko šele izbiramo glede na zahteve ustrezno merilno opremo. Upoštevajoč dobljene vrednosti opravljenih izračunov lahko povzamemo, da je merjenje tokov enofaznih fluidov s standardizirano ostrirobo merilno zaslonko zadovoljivo z vidika merilne negotovosti. Pri tem pa morajo biti izpolnjene naslednje temeljne zahteve:

- ostriroba merilna zaslonka kot primarno zaznavalo mora biti dimenzionirana po veljavnih in v standardih [6] predlaganih matematičnih modelih;

- merilna zaslonka in drugi elementi merilnega sistema morajo biti pravilno vgrajeni ob upoštevanju tokovnih, geometrijskih in obratovalnih razmer ter mesta vgradnje;

- tokovni pretvornik tlačne razlike mora dosegati ustrezno merilno točnost.

Tako bomo dosegli zadovoljivo merilno točnost masnega toka fluida za industrijsko uporabo (od 1,5 do 2 odstotkov), kjer se merilna zaslonka tudi največ uporablja. Ker smo se v našem prispevku omejili le na primarno in sekundarno zaznavalo, je treba k merilni točnosti dodati še določen delež, ki ga prispevajo drugi elementi merilne verige (prenos in prikaz informacij), ki pa zaradi vse večje izpopolnjenosti elektronske opreme ni bistven.

4 CONCLUSION

Measurement uncertainty analysis is a helpful tool in all phases of experimental work, particularly in the planning phase of an experiment, when we only choose the appropriate measuring equipment according to our requirements. Considering the calculated values we can conclude that the measurement of one-phase fluid flows with a standardized square-edged orifice plate is satisfactory concerning the measurement uncertainty. But we have to fulfill the following requirements:

- the square edged orifice plate as the primary sensor has to be dimensioned according to the valid mathematical model also recommended in the standard [6].
- the orifice plate and other elements of the measuring system have to be installed correctly considering the geometry, the flow and operating conditions of the system.
- the current transmitter of pressure difference must have an appropriately high accuracy of measurement.

In this way we can achieve satisfactory mass fluid flow measurement uncertainty for industrial use (between 1.5 and 2 percent), where the orifice plate is used most frequently. Because in our paper we have restricted ourselves only to dealing with the primary and secondary sensors, we have to add a certain part to the accuracy of measurement contributed by other elements in the measuring chain (transfer and display of information), but this is not essential because of constant improvement in electronic equipment.

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