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Tracer flowmeter with a conductive sensor

Abstract. *This paper presents a research installation for developing flow measurements in open channel. A tracer technique is used where sodium chloride is applied as a tracer and a conductometric cell as a tracer sensor. Properties of the applied electrical measuring circuit, the ways of determining tracer transit time, flow rate and flow velocity are described. From conducted experiments, the expanded measurement uncertainty of flow rate is assessed as less then 6%.*

Streszczenie. *W niniejszym artykule przedstawiono stanowisko laboratoryjne przeznaczone do badań nad metodami pomiaru strumienia objętości w kanałach otwartych. Zaprezentowano znacznikową metodę pomiaru z wykorzystaniem chlorku sodu oraz czujników konduktometrycznych jako jego detektorów. Przedstawiono również układ do pomiaru sygnałów z czujników konduktometrycznych, a także sposób wyznaczania czasu przejścia znacznika pomiędzy punktami pomiarowymi. Przeprowadzone eksperymenty pozwoliły uzyskać wyniki pomiaru strumienia objętości z niepewnością na poziomie 6%.* ***(Przepływomierz znacznikowy z czujnikiem konduktometrzycznym)***

Keywords: flow measurement, tracer method, flowmeter calibration
Słowa kluczowe: pomiar strumienia objętości, metodza znacznikowa, wzorcowanie przepływomierzy

Introduction

There are above one hundred methods of measuring the flow rate of a substance. Among them, a tracer method exists. It is particularly useful when a channel can not be closed and when there is no way to mount a classic flowmeter such as flume [1]. The concept of the transit time method is very simple – a tracer is added to a stream and a time period of passing of the tracer between two (or more) detectors is controlled and then flow velocity or volumetric flow is determined. If the profile of the channel is known, volumetric flow rate can also be calculated [1, 2, 3, 4].

Any number of substances can be used as the tracer. Their physical or chemical properties allow one to detect their presence. Suitable detectors should also be applied. Optical detectors allow one to measure colouring or transparency of the medium; heat detectors – its temperature; ionizing radiation detectors – presence of radioactive substances; finally, the conductometric detectors – change of liquid conductance. Furthermore, tracers should satisfy additional requirements such as good mixing ability with water [5].

The conductive method of the tracer flow measurement is not expensive and does not influent significantly on the natural environment. This study describes a measurement circuit with the flowmeter applying in the method and presents results of preliminary tests.

Artificial channel

In order to conduct the research on open channel flowmeters, an artificial channel has been build in the laboratory. A four meter length semicircular gutter was used as a channel. The gutter diameter is seventy millimetres. The channel is directly connected to and it is fed form an installation dedicated to the flowmeter calibration in closed conduits (Fig. 1). Several flowmeters are mounted on the set-up. Each of them can be calibrated and used as a reference flowmeter. The water cycle is forced by a water pump which has ten cubic meters per hour efficiency. Volumetric flow rate in the pipeline can be regulated using a precise valve which changes a flow in the shunt. There are also two tanks: the first one is a water reservoir while the second one is a calibrated tank which is used as a volume standard during calibration of the flowmeters using the volumetric method.

The water circulation using the build artificial channel is proceeded as follows: water is pumped by a pump from the reservoir tank through a pipeline and mounted on it flowmeters. Next, it flows into the channel, from which flows into a small buffer tank and finally goes back to the reservoir (a second pump is used). The red arrow in Fig. 1 marks the water flow direction.

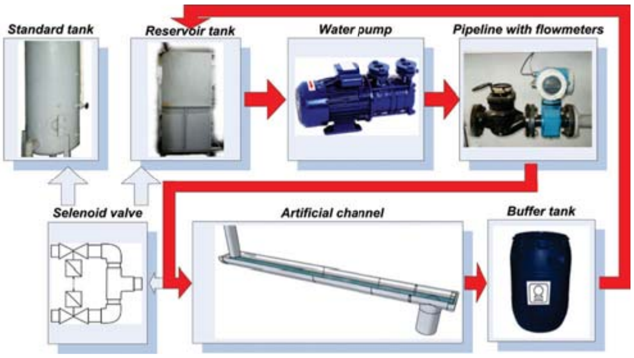

Fig. 1. Schema of the laboratory set-up

Water level and flow velocity in the artificial channel are correlated. If flow velocity is rising, water level in the channel is rising, too. There are three ways to stabilize the quantities. The first one: slope of the gutter can be regulated, the second one: flow velocity of the outgoing water can be changed by a gate valve, and finally the third one: volumetric flow rate in the water circuit can be regulated using a precise valve. After setting the desired flow rate, it is needed to wait until the steady state is obtained in the channel. After that, the water level and flow rate values can be read out.

Measuring set-up

An installation to the tracer transit time measurement has been mounted on the artificial channel. The installation consists of:

- a tracer dispenser – mounted at the beginning of the channel,
- a water level gauge – mounted at the tracer sensors,
- a system recording tracer concentration.

The most complicated part is the system for the tracer concentration acquisition and it consist of: tracer detectors – electrochemical cells, a conductance to voltage (G/U) converter, a DAQ card and a computer with the LabVIEW environment (Fig. 2). The Promag 30F electromagnetic flowmeter is also used as a reference flowmeter during the measurements.

Concept of measurement

The measuring principle is very simple: a tracer is injected into water and then tracer concentration changes are recorded at two or more measuring points. Transit time is obtained by comparing answers of the concentration detectors

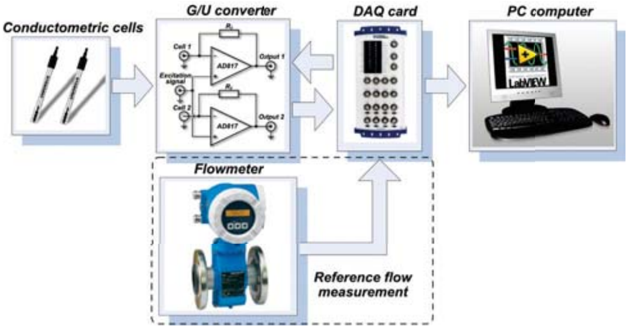

Fig. 2. Schema of measurement system

over time. To calculate the volumetric flow rate value, it is also necessary to know flow cross-sectional area which is a function of water level.

Each measurement experiment is performed in the same way. After obtaining the steady state in the channel, water levels at the tracer sensors is measured, the tracer is injected and signals from tracer detectors are recorded. The results of the measurements make two (or more) curves of the tracer concentration changes over time. The next step is the data analysis and the volumetric flow rate calculation. From the curves, the transit time value is determined. To obtain the transit time, it is also necessary to determine characteristic points on the curves presenting tracer concentration changes. It can be the maximum values. Flow velocity v is calculated from:

$$v = \frac{D}{\Delta t} \tag{1}$$

where D is distance between the tracer detectors and Δt is transit time.

Volumetric flow rate q_v can be calculated from:

$$q_v = \frac{kDA}{\Delta t} \tag{2}$$

where k is a calibration factor and A is cross-sectional area.

The calibration factor k describe the ratio of average flow velocity at the point where cross-section is measured to flow velocity determined between the tracer detectors according to (1). In addition, to get credible value of flow rate, the following conditions have to be fulfilled:

- the tracer is completely mixed with water at the first measuring point,
- cross-sectional area is obtained enough accurate,
- distance between the detectors should be long enough to provide sufficient measurement accuracy of transit time but short enough so as not to blur the tracer [6].

Tracer sensors

In the elaborated method, a sodium chloride solution has been chosen as a tracer changing conductance of water. The changes are detected by at least two sensors. Electrochemical cells are used as the conductance sensors. A typical conductivity cell consist of two electrodes and a chamber of known volume. The electrodes are usually made of a platinum foil and coated with a platinum black. The material is very often used to overcome problems with electrode kinetic overpotential [7, 8]. In the tests, two *EPS 2ZM* electrochemical cells, purchased from Zakład Produkcji Elementów Aparatury Fizykochemicznej *Eurosensor*, Gliwice, Poland are used as the tracer detectors. In the experiments, tracer concentration is changed rapidly, so it is necessity to register quick changes of water conductance. The transit time measurement methodology does not require accurate measurements of tracer concentration but it is required to register nature of the changes. A typical conductance sensor consists of a chamber which worsen measurement dynamics. The chambers has been removed in the applied sensors. In the way the dynamics of the sensors increase but the measurement accuracy of concentration is reduced.

G/U converter

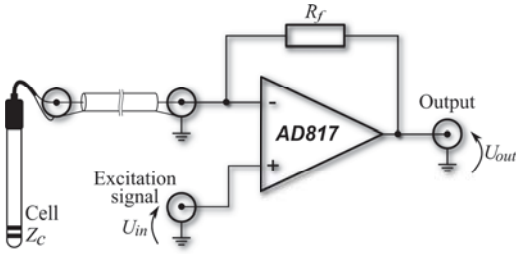

Fig. 3. Circuit of the conductance to voltage converter connected to a conductometric cell

To measure liquid conductance by a data acquisition system, the conductance of water has to be converted to voltage. However, conductance is only one of components measured at the cell connectors. Due to the existence of double layers between metals and liquid, it is only possible to measure whole impedance (complex value) of the cell containing also the conductance of interest [8]. Using alternative voltage as an excitation signal, it is possible to get:

$$Z_C \approx \frac{1}{G} \tag{3}$$

where Z_C is cell impedance and G is conductance of water in the cell. As the G/U converter, it has been decided to use an operational amplifier in the non-inverting circuit (Fig 3). The output voltage U_{out} of this circuit is:

$$U_{out} = \left(\frac{R_f}{Z_C} + 1 \right) U_{in} \tag{4}$$

where R_f is feedback resistance and U_{in} is excitation signal (voltage).

The following tasks have to be done at the designing stage:

- determination of the converter measurement range,
- determination of the frequency of the excitation signal (an alternative voltage is used to minimize effect of electrode polarization),
- choice of the amplifier.

The conductivity of the water in the installation is chosen as a minimum value in the system. Feedback resistance is set to such a value to obtain amplifier gain about two when the sensor is immersed in the water. Conductivity of the concentrated solution of the tracer ($100\ \mathrm{g\ NaCl}/1\ \mathrm{dm}^3\ \mathrm{H_2O}$) is assumed as the maximum measured value. The gain of the circuit is about 56 when the sensor is put in the concentrated solution. The gain is high enough to go into the amplifier saturation for 400 mV amplitude of the excitation signal. In practice, such high concentrations of tracer does not occur, because of the tracer dilution in water and therefore there is no problem with the saturation.

The sensor properties determine the frequency of the excitation signal. The conductometric cell can be replaced by an equivalent electrical circuit. Simplifying, each electrode can be represented by a parallel combination of a double layer capacitance and non-linear resistance. In series, between electrodes is the ohmic resistance of the electrolyte connected parallel with the capacitance arising from both electrodes. For each electrochemical cell such frequency of the excitation signal can be found for which the resistive component of the cell is dominant [9].

To determine the proper frequency of the excitation signal, the Bode plots for various tracer concentration (from the distilled water to the concentrated solution of the tracer) have been performed (Fig. 4). It can be deduced from the magnitude plot that the circuit has the appropriate gain for frequencies above 10 kHz. In turn, a phase delay can be observed in the desired range in the phase plot. However, the phase not influence measurement results.

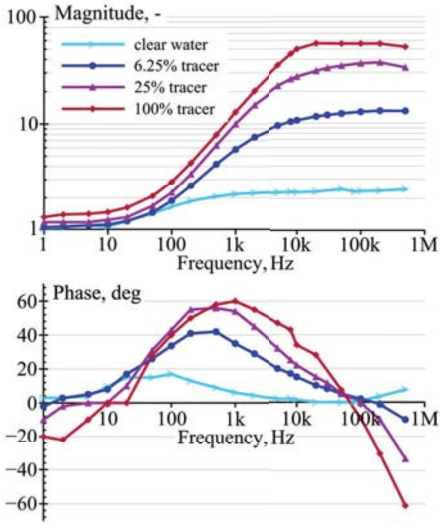

Fig. 4. Bode plots of the conductometric cell connected to the G/U converter for various concentration of the tracer

Because the frequency of the excitation signal is relatively high, the bandwidth of the op-amp used has to be wide, too. Therefore, the Analog Devices AD817 op-amp has been chosen.

Data acquisition

The measuring set-up works with the National Instruments NI-USB 6212 DAQ card and a software written in LabVIEW environment. The main task of the programme is the data acquisition from the G/U converter. It also enables the data acquisition of the reference flowmeter and records measuring conditions such as: liquid levels at the tracer detectors and volume of the injected tracer. The programme also allows user to generate the excitation signal. After measurements, results are saved to a text file. Such a solution allows for subsequent data analysis.

Experiment

Each experiment consists of the following steps: (1) the level measurement at two points, (2) the tracer injection and (3) the data acquisition of conductivity and reference flow rate. Five series have been done, each of them consists of ten measurements. From the results, volumetric flow rate has been obtained.

Calculation of the cross-sectional area

The used channel model has semicircular cross-section. In order to calculate cross-sectional area of the stream, the channel cross-section has been approximated to an ellipse. For this purpose, channel chords in five different places have been measured. At every point, ten measurements of chord across the channel have been made. Based on the results of measurements, ellipse parameters have been estimated. Cross-sectional area A is calculated from the following formula:

$$A(L) = 2 \cdot \int_{(x_0+b)-L}^{x_0+b} \sqrt{b^2\left(1-\frac{(x-x_0)^2}{a^2}\right)}dx \tag{5}$$

where: L – water level, a – semi-major axis, b – semi-minor axis, x_0 – horizontal shift of the center of the ellipse (Fig. 5a). Water level in the channel is measured in two points at the tracer detectors. Their mean value is used in the cross-sectional area calculations using formula (5). In-house fabricated screw water level gauge (Fig. 5b) is used to measure the water level. The measurement principle as follows: the M6 screw is screwed up until its tip touches the water surface. One full rotation corresponds with one millimetre of the tip displacement.

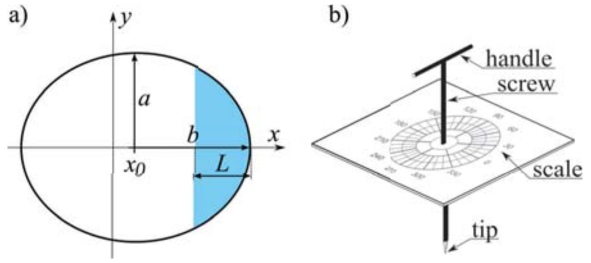

Fig. 5. Determination of cross-sectional area of the stream: a) illustration of symbols applied; b) a scheme of the screw water level gauge

Transit time and calibration factor calculation

The curves presenting tracer concentration changes in two measuring points are obtained in each experiment. Based of them, tracer transit time is calculated. It is the time difference between characteristic points on the curves. The ISO standard [5] provides a number of ways to determine the characteristic points and the transit time such as: centre of gravity concentration curve and peak maximum. These methods do not work well because of signal noises from the tracer detectors.

We prefer another method to determine the transit time. It is based on the estimation of the parameters of the peak model previously established. In previous publication [10], the authors have tested different models of the peaks. The best fit to the signals received from the tracer detectors have been obtained for the polynomial modified Gaussian function which is given by:

$$L(x) = h \exp\left[\frac{-x-t_m}{2(w_1+w_2x)^2}\right] \tag{6}$$

where: h – height of the peak, t_m – time of peak maximum, w_1, w_2 – parameters describing peak width.

Such a solution has many advantages such as: (1) possibility of the accurate determination of the characteristic points and tracer transit time, (2) description of the tracer concentration curve as a continuous function and (3) no need to filter the signal obtained from the tracer detectors.

Selecting various ways of determination of the characteristic points, the value of calibration factor k (in Eq. 2) changes and therefore the flow velocity also changes. Transit time, which is calculated as the time period between origins of the peaks, should correspond to the maximum velocity of the stream in the channel. The best solution is to find such a characteristic point for which the transit time corresponds to average velocity. In this case, the k factor should be one.

In the first approach, the calibration factor k has been obtained in an experimental way. Five measurement series have been performed, each consist of ten measurements. Individual series have been made under different conditions: the value of flow rate (of range: 0.7—1.5 m^3/h), distance between measuring points (0.5—1.5 m) and the amount of injected tracer (5 or 10 ml) have been changed. The tracer detectors always were located at half height of water level. On the basis of the all results, the average value of k and its standard deviation were calculated for the following characteristic points: PM – peak maximum, BP – beginning of the peak, CG – centre of gravity concentration curve, HA – half-area point, PH – part-height point. Formulas for the mentioned points are given in ISO standard [5]. The results are presented in Table 1.

Table 1. Average values of the calibration factor k calculated for various ways of determining the characteristic points. Abbreviations – see text

	PM	BP	CG	HA	PH
mean value	1.08	0.84	1.26	1.25	1.17
standard deviation	0.08	0.09	0.13	0.14	0.09

It can be concluded from the results that PM gives the best results. The obtained calibration factor k is the closest to one and has the lowest standard deviation. The additional advantage is an insensibility to changes in measurement conditions (*eg.* flow rate). For some series, very good results were obtained for CG, however, this method is sensitive to the change in the amount of injected tracer – hence bad final result.

In order to verify experimental results, the theoretical value of the calibration factor k is determined. For that, it is assumed that the channel has a circular cross-section and that the water level is equal to the radius of the cross-section. The assumptions are justified because the ellipse semiaxes differs not significantly and the consideration are only for finding the variety of the flow rate in relation to the sensor depth. To calculate the flow velocity distribution in the channel, the Prandtl model is used [11]:

$$v(r) = v_m \left(1 - \frac{r}{R}\right)^{\frac{1}{n}} \tag{7}$$

where: v – local velocity value, v_m – maximum velocity, r – depth of the detector measured from the centre of the channel, R – channel radius, n – exponent depending on the Reynolds number.

Based on the above mentioned assumptions and the Prandtl model, the plots of the calibration factor k versus detector depth and the n exponent have been calculated (Figs. 6 and 7). As it can be concluded, the calibration factor k is more sensitive to changes in the position of the detector than to changes in the n exponent. In addition, by setting of sensor at $0.55\,R$, the value of the calibration factor k is independence of the n exponent. It means that in the position changes in the flow rate have minimal impact on the value of the calibration factor.

Theoretical value of the calibration factor k, calculated for the position of the sensor in the middle of the radius of the channel (such as during the experiments) is in the range of 0.951—0.978. None of the values obtained experimentally fall within the range. It is due to the fact that the time period, measured between the characteristic points, includes the fluid velocity and tracer dispersion. The value of the calibration factor k calculated basing on the peak maximum is the nearest to the theoretical range and it also has the smallest standard deviation. Therefore, it is used in further calculations.

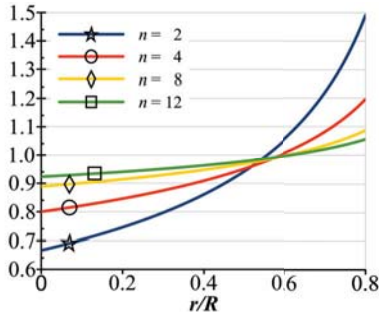

Fig. 6. The dependence of the calibration factor k on the r/R ratio

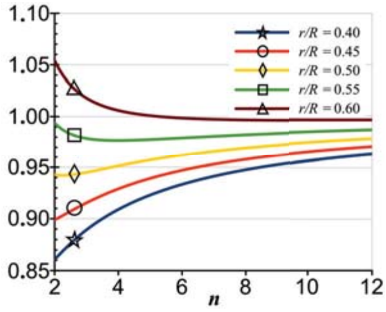

Fig. 7. The dependence of the calibration factor k on the n exponent

Final result and uncertainty evaluation

The final step is executing the measurement series, calculating the value of volumetric flow rate and estimating the measurement uncertainty. For this purpose a series of ten identical measurements have been performed where position of the first detector is at $Z = 0.8$ m and the distance between the detectors is $D = 0.6$ m. Transit time of the tracer is calculated as the time difference between the peak maxima. The obtained mean value of the flow rate is $0.92\,\mathrm{m}^3/\mathrm{h}$, and the standard deviation is $0.05\,\mathrm{m}^3/\mathrm{h}$.

Individual uncertainty components are estimated in order to estimate the uncertainty of volumetric flow rate. The value is calculated according to (2). Therefore, the uncertainties of the calibration factor k, of the distance between detectors D, of the cross-sectional area A and of the transit time Δt should be estimated. Due to the fact that the calibration factor is determined experimentally, its standard deviation obtained from the results is assumed as the uncertainty. It is possible to estimate the uncertainty of k in the theoretical way by analysing the possible models of velocity distribution in the channel. The theoretical background for this problem is presented elsewhere [12, 13]. To calculate the uncertainty of distance D, the ± 5 mm distance measurement error and a rectangular distribution of the errors are assumed. To calculate the water level uncertainty (needed to determine cross-sectional area), the ± 0.5 mm measurement error and a rectangular distribution of the errors are assumed. To determine the uncertainty of cross-sectional area A, a total derivative of Eq. (5) is calculated. For transit time, the statistical uncertainty of a series of measurements is estimated. Relative uncertainty of individual components and the relative combined uncertainty of the volumetric flow rate measurement for a single measurement of a series are gathered in Table 2. Basing

Table 2. Relative measurement uncertainties of components needed to calculate the uncertainty of flow rate

$u_r(k)$	$u_r(L)$	$u_r(A)$	$u_r(\Delta t)$	$u_r(q_v)$
1.1%	0.48%	1.5%	2.0%	2.8%

of the results, it can be concluded that the greatest impact on the volumetric flow rate uncertainty using the tested method has the uncertainty of transit time. The uncertainties of the calibration factor and of cross-sectional area have also significant influence. The uncertainty of the distance between the detectors has negligible impact compared to other components. Assuming the coverage factor equal to 2, the obtained expanded relative uncertainty is less than 6%. This result is quite good comparing with other methods of flow rate measurements.

The uncertainties of the standard flowmeter readouts are obtained by combining the uncertainty components obtained from Type A and Type B evaluations. The result of the Type A evaluation of the uncertainty (statistical one) is determined from a series of measurements while the result of the Type B evaluation arises from the uncertainties of individual measuring devices mounted on the calibration installation. The estimated expanded relative uncertainty of the standard flowmeter is 0.6%. It means that the standard accuracy is one order better then accuracy of performed measurements.

The final results of the volume flow measurements with their uncertainties are presented in Table 3. Two of ten measurements did not coincide with indications of standard flowmeter.

Table 3. Comparison of result obtained by the elaborated method with indications of standard flowmeter expressed in m^3/h

No.	q_v	$U(q_v)$	$q_{v\,\min}$	$q_{v\,\max}$	q_s
1	0.921	0.052	0.869	0.973	0.918
2	0.929	0.052	0.878	0.981	0.912
3	0.922	0.051	0.873	0.975	0.911
4	0.924	0.051	0.872	0.975	0.911
5	**0.811**	0.045	0.766	0.856	0.905
6	0.954	0.054	0.900	1.007	0.900
7	0.945	0.053	0.893	0.998	0.896
8	**0.990**	0.056	0.934	1.045	0.897
9	0.901	0.050	0.850	0.951	0.895
10	0.943	0.053	0.890	0.996	0.893

Symbols: q_v – volumetric flow rate obtained by the tested method, $U(q_v)$ – expanded uncertainty of volumetric flow rate, $q_{v\,\min}$ and $q_{v\,\max}$ – limit values of flow rate, q_s – average value of volumetric flow rate of the standard flowmeter.

Conclusion

In the paper, we have studied the tracer transit time method of the volumetric flow rate measurement. All aspects of the method are analysed precisely. A new method for determining tracer transit time has been proposed. Uncertainties of the measurements using the elaborated method have been estimated and test measurements have been carried out.

The obtained 6% expanded uncertainty of the volumetric flow rate measurements performed using the elaborated method is comparable to results obtained using other methods of volumetric flow rate in such open channels as flumes or weirs. An important advantage of the tracer methods is that there is no need to build a complex measuring infrastructure. However, the transit time method requires the determination of flow cross-sectional area, the measurement of water level and regular shape of the channel. Despite these limitations, this method can be used to test various flow measurement methods applied under difficult conditions, in which other methods are not applicable or their costs are much higher than cost of the method introduced in this paper.

Author thanks the Polish Ministry of Science and Higher Education for financial support.

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