Open-channel Discharge Measurement based on Ultrasonic Doppler Velocity Profiling – Laboratory Experiments

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Presented study deals with the design, the experimental evaluation and the verification of the novel methodology for open-channel discharge measurement suitable especially for the short-term monitoring. The methodology is based on an error-minimized application of ultrasonic velocity profiling method enabling the measurement of instantaneous velocity distribution over the entire flow depth without direct contact with the flowing liquid. The total relative bias of measured and reference values of the discharge from all experiments was 3.2 %. Results show that the relative error increases with the flow depth. The second group of experiments introduces more or less stable results. Besides the total value of discharge, the method also offers detailed information about velocity distribution over the cross section. The influence of side walls on the velocity distribution in verticals close to the channel walls is clearly stated. The neglecting of that effect in classical flow metering techniques contributes to wrong estimation of depth-averaged velocity. The results show high accuracy of presented flow rate measurement methodology and demonstrate its great potential to identify hydraulic singularities in open-channel flows.

Keywords: Discharge measurement; open-channel flow; ultrasonic anemometry; velocity profile

1 INTRODUCTION

The information about the inflow/outflow at the waste water treatment plant (WWTP) is one of the fundamental parameters of performance data to control treatment process and maintenance of the WWTP [1]. Simple measuring devices such as weirs or flumes are accurate enough, however their calibration is needful. The uncertainty of the calibration method often exceeds the uncertainty of the measured flow rate given by measuring weir. The sources of the uncertainty are the human factor, the influence of the velocity field with the measuring device used for calibration (propeller), the flow non-uniformity and unsteadiness, the measuring time and the accuracy of the measuring device (propeller) itself. Presented study deals with the design, experimental evaluation and verification of a novel methodology for open-channel discharge measurement suitable especially for short-term monitoring. The methodology is based on an error-minimized application of ultrasonic velocity profiling method enabling the measurement of instantaneous velocity distribution over the entire flow depth without direct contact with the flowing liquid.

2 EXPERIMENTAL METHODS

2.1 Measuring devices

The methodology was tested under laboratory conditions in a rectangular flume of width of B= 0.525 m and length of L = 8 m. The reference values of the total discharge were obtained using MID flowmeter (Krohne Aquaflux DN 200) at inlet pipe of the flume. A calibrated ultrasonic transducer (Pepperl&Fuchs UC2000) was used for measurement of flow depth. The information about the velocity distribution in the channel was obtained using Ultrasonic Velocity Profiler (Met-Flow SA) together with employing of two ultrasonic transducers (basic frequency f_0 = 4 MHz, active diameter d = 5 mm, sampling frequency f = 12.5 Hz, sampling time of one TDX t = 120 sec).

2.2 Hydraulic conditions

Experiments were carried out under different flow conditions in turbulent (Re = 1.94×10^4~1.34×10^5) and subcritical (Fr = 0.05~0.54) flow regime. In the first group of experiments a constant flow depth of h = 228 mm was maintained in the channel and the flow rate varied in the range of Q = 10 ~ 60 l/s with step of $\Delta Q \cong 10$ l/s. The second series of experiments was carried out with a constant flow rate of Q = 29.5 l/s and a varying flow depth h = 100 ~ 410 mm with step $\Delta h \cong 80$ mm. Velocity distribution was measured in 11 verticals in each experiment.

2.3 Discharge estimation

The method used for discharge estimation is a modification of the classical hydrometric technique for flow rate measurement, the so-called *area-velocity method*. [2]. In contrast to propeller gauging, the depth-averaged velocity is estimated based on numerical integration of time-averaged velocity profile over flow depth h with spatial resolution of Δy = 2.22 ~ 4.4 mm.

To minimize possible errors, several critical aspects of UVP method [4] were taken into account. Measurements were made using two independent probes in one vertical with inclination of $\theta = \pm 20°$ to vertical axis [3]. The transducers were placed in a movable box made of plexiglas (Figure 1). Such positioning can minize the error originating from non-uniformity of the flow (vertical and horizontal velocity components are identifiable) and the error from wrong setting of the box instalation. The box is filled with water and the bottom is made of PVC film (th. 0.1 mm). That allows the positioning of the near field of the US beam out of the flowing liquid.

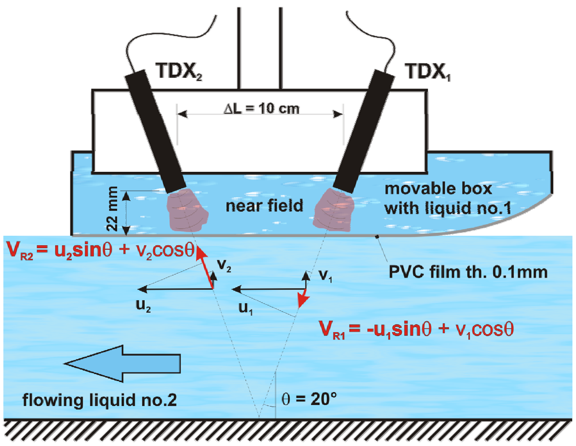

Figure 1: Scheme of transducers position and velocity vector decomposition

Assuming small distance (ΔL = 10 cm) between the heads of transducers compared to the length of the channel, the time-averaged longitudinal velocity components are equal to each other at the same horizontal level.

$$\bar{u}_{1j} \approx \bar{u}_{2j} \approx \bar{u}_j \tag{3}$$

where indexes <1;2> identify a US transducer and index j = <1;11> a given vertical. Based on Figure 1 one can write expressions for time-averaged vectors in direction of radial axis of US probes as:

$$\bar{V}_{R1j} = -\bar{u}_{1j}\sin\theta + \bar{v}_{1j}\cos\theta \tag{4}$$

$$\bar{V}_{R2j} = \bar{u}_{2j}\sin\theta + \bar{v}_{2j}\cos\theta \tag{5}$$

Further, one can easily express longitudinal component of point velocity as:

$$\bar{u}_j = \frac{\overline{V_{R1j}} + \overline{V_{R2j}}}{2\sin\theta} \tag{6}$$

Integrating the measured values of point velocities over flow depth h and channel width B one can estimate discharge in cross section as:

$$Q = \int_0^B \int_0^h \bar{u}_j \, dydx \tag{7}$$

3 RESULTS

3.1 Velocity profiles

Eleven vertical profiles were measured for each given discharge (Figure 2). It is clearly visible that the velocity distribution in a cross section is highly asymmetrical to vertical axis (Figure 5). The velocity distribution itself significantly deviates from vertical to vertical and it cannot be described by a general valid formula. Obviously, the velocity profiles in verticals close to side walls are less than in the centerline.

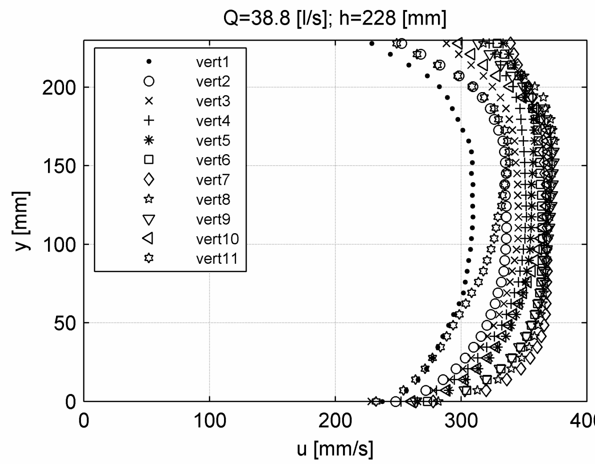

Figure 2: Time-averaged velocity distribution of longitudinal velocity component in given verticals for run Q40_h22 (Q = 38.8 l/s; h = 228 mm).

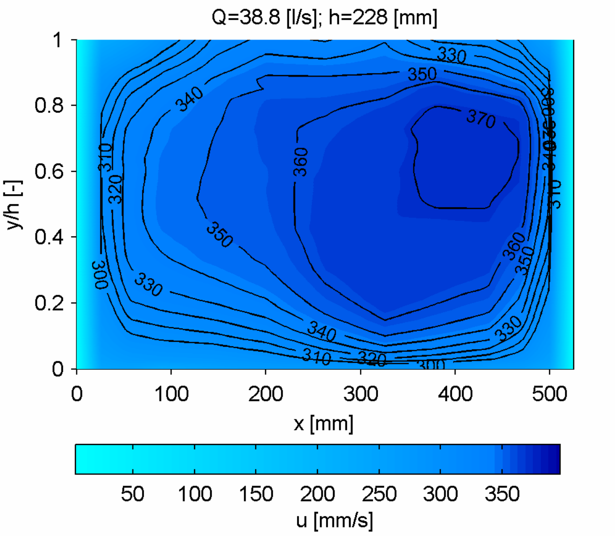

Figure 3: Distribution of longitudinal velocity component in cross section for run Q40_h22 (Q = 38.8 l/s; h = 228 mm).

3.2 Total discharge

Summarized values of estimated flow rates are presented in Table 1 with values of discharge measured using MID (Q_{KR}) taken as reference values. Absolute and relative errors vary in the range from 0.51% to -5.93%. The average relative error was estimated as -3.22%.

Table1: Results of measured flow rates with absolute and relative errors (100% ≈ MID Krohne).

Run	Δy [mm]	h [mm]	U_{Kr} [mm/s]	U [mm/s]	Q_{Kr} [l/s]	Q [l/s]	T [°C]	Fr [-]	Re [-]	abs. error [l/s]	rel. error [%]
Q10_h22	2.22	231	82.48	81.42	9.99	9.87	16.2	0.05	19463	-0.11	-1.12
Q20_h22	2.22	229	168.01	163.13	20.22	19.61	16.2	0.11	39646	-0.61	-2.99
Q30_h22	2.22	229	248.87	241.26	29.98	29.01	16.3	0.17	58874	-0.98	-3.26
Q40_h22	2.22	228	334.11	324.29	40.06	38.82	16.3	0.22	79039	-1.25	-3.11
Q50_h22	2.22	228	416.74	403.33	49.87	48.28	15.9	0.28	97601	-1.59	-3.19
Q60_h22	2.22	228	502.32	483.45	60.11	57.87	15.9	0.34	117643	-2.24	-3.73
Q29_10	1.48	104	543.80	546.57	29.69	29.84	15.6	0.54	126187	0.15	0.51
Q29_18	2.22	194	292.03	282.76	29.69	28.80	15.6	0.21	67843	-0.89	-3.00
Q29_26	2.96	251	222.68	212.64	29.38	28.02	15.8	0.14	52020	-1.36	-4.62
Q29_34	3.7	337	167.62	159.12	29.62	28.15	15.9	0.09	39270	-1.47	-4.97
Q29_41	3.7	411	136.26	128.28	29.42	27.68	15.9	0.07	31928	-1.74	-5.93

Note: Δy = channel distance; h = flow depth; U_{KR} = average velocity in cross section (MID); U = average velocity in cross section (UVP); Q_{KR} = discharge (MID); T = water temperature; Fr = Froude number; Re = Reynolds number.

Figure 4 and Figure 5 represent the relationship between rel. error and averaged velocity in the cross section *U* resp. flow depth *h*. The relative error seems to be constant (≈ -3%) over a wide range of velocities (150 ÷ 500 mm/s), with the exception of velocity *U* = 80 mm/s (run Q10_h22). In case of flow depth *h* (Figure 5), the relative error increases continuously with increasing flow depth up to almost -6%. Comparing two runs (Q30_h22 and Q29_18) with similar flow conditions one can observe a similar relative error of measured flow rate (≈ -3%).

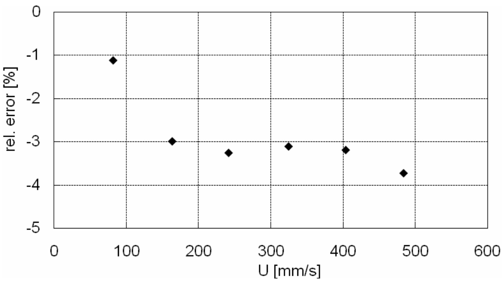

Figure 4: Relationship between the relative error of measured discharge and the average velocity in a cross section.

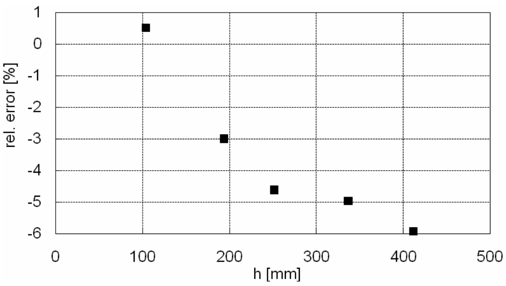

Figure 5: Relationship between the relative error of measured discharge and flow depth.

4 DISCUSSION

4.1 Depth-averaged velocity

The main advantage of UVP measurements related to discharge estimation is the information about vertical velocity profile with high spatial resolution. This contrasts with hydrometric methods, which usually use point measurements with probes, propellers etc. Comparison of measured and estimated depth-averaged velocity is presented in Table 2. The depth-averaged velocity of *U* was estimated by numerical integration of measured profile using UVP. The averaged velocity in vertical U_v was estimated using the following equation valid for 5 point measurements:

$$\overline{U_v} = 0.1\left(u_b + 2\, u_{0.2h} + 3\, u_{0.4h} + 3\, u_{0.8h} + u_s \right) \quad (8)$$

where u_b is velocity on the bottom, u_h is point velocity in a given level *h* and u_s is the point velocity at water surface.

Table 2 shows that the highest deviation belongs to verticals close to side walls and it decreases towards the centerline of the channel. This corresponds with theoretical considerations.

4.2 Measuring box

The use of the measuring box was found profitable. One doesn't lose velocity data belonging to near field of US beam close to the water surface. Further, the box influences flowing liquid much less than probes placed directly in the water. Moreover, the box minimizes the possibility of clogging of transducer which is a significant difficulty especially in waste water. All experimental runs were made twice (with and without box). Averaged relative error for runs without box was –4.5%, which is more than with the box (Table 1).

Table 2: Deviation between measured and theoretically estimated depth-averaged velocity for given verticals (run Q40_h22).

vertical	U [mm/s]	U_v [mm/s]	rel. error [%]
1	291.0	284.9	2.10
2	317.5	311.8	1.80
3	327.4	320.5	2.13
4	336.5	332.4	1.20
5	344.0	340.8	0.93
6	352.5	348.0	1.26
7	358.8	353.9	1.35
8	358.8	353.4	1.50
9	354.9	348.9	1.68
10	344.9	339.4	1.61
11	307.8	301.4	2.07

4.3 Duration of measurement

When the discharge is measured during a field investigation, one of the important criteria is the duration of the measurement. It is obvious that in systems where the flow rate changes relatively fast (i.e. waste water systems) this can influence the result of hydrometric measurement significantly. Using our experiment as example, the appropriate time for classical hydrometric method using a propeller in 55 positions in the cross section and a measuring time of 1 min per each point would be more than 1 hour. Employing the multiplexer function on UVP Monitor and an appropriate number of US probes one can estimate the flow rate in such channel in 22 minutes (in simplified approach with 1 probe per vertical in 11 minutes), which is significantly shorter.

4.4 Sensitivity to Doppler angle

One of the disadvantages of the UVP method is a high sensitivity of measured mean flow velocity to the setting of correct Doppler angle. The deviation of probe installation by θ = ±1° in presented experiment (θ = 20°) produces an error of ± 5% in the estimated discharge. The probability of deviation during in-situ measurement is very high. Therefore, two transducers fixed in steel element were used for velocity measurements. That minimizes the error originating from wrong installation of the whole apparatus.

5 CONCLUSION

Introduced flow metering technique based on non-invasive measuring of velocity distribution in selected verticals provides accurate information about discharge, takes into account specific velocity distribution in verticals, and allows to obtain detailed information about the velocity distribution in a cross section. Averaged relative error was evaluated as -3.22%. The error is independent on averaged velocity in cross section *U* and is significantly influenced by flow depth *h*.

In respect to classical hydrometric methods it is concluded that even in laboratory rectangular flume the estimation of depth-average velocity using point measurement introduces significant source of error. That would be expected in natural streams as well.

In addition, the experiment revealed a previously unknown asymmetry of measuring flume in the laboratory.

The methodology itself cannot replace classical hydrometric methods for discharge estimation, it would, however, be preferable in specific cases.

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