Flow measurement methodology for low head and short intake bulb turbines - Iron Gate 2 case

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Abstract

Flow measurement of low head turbines, with short intakes like bulb turbines is challenging since there is no "regular" cross-section with fully developed velocity profile. In most situations the flow data during field turbine acceptance tests are obtained using the index method, with flow coefficients transferred from physical model tests done in the laboratory. In the non-standard situations, with adverse flow conditions this may lead to unpredicted flow rate uncertainty. This paper presents the used methodology and results of flow measurement at inlets of two bulb turbines of Hydro Power Plant (HPP) Iron Gate 2 (Danube river). Turbines are Kaplan, with low head (2.5 – 12.5 m), 27 MW and maximal flow rate 420 m^3/s. Due to HPP's disposition the inflow angle (in a "horizontal" plane and in respect to the turbine axis) can be up to 40^0. Even reverse flow directions in upper regions of cross-section can occur. The movable 14.5x3.1 m steel frame, shaped to minimize flow disturbances was used at the intake of turbine, upstream of the trash rack, to traverse the inflow cross section 14.5x26 m. The 15 spherical 3D electromagnetic velocity meters capable of bi-directional measurements were mounted on the frame, while redundant measurement were made using 2 ADVs. Two measurement strategies were used: incremental with 18 profiles and 10 min averaging time at each profile and continuous using constant lifting speed of 0.05 m/s. Uncertainty assessment procedure yielded discharge measurement uncertainties over 1 % for incremental, and up to 5 % for continuous traversing.

1. Introduction

The in-situ flow (or discharge) measurement of low head turbines with short intakes like bulb (or tubular) turbines is always a challenging task since no "regular" measuring cross-section, with parallel and symmetric flow, with low turbulence and without swirls, can be found. Because of that, in most situations the field turbine acceptance tests are based only on the flow data measured with the index method (like Winter-Kennedy) using the flow coefficient(s) established on the physical model. Even in the standard situations the lack of in-situ direct flow measurement is not the best idea [1], and in the non-standard configurations, with adverse flow conditions, this may lead to unpredicted flow rate uncertainty.

The IEC-EN 60041 standard [2] is not directly applicable for flow measurements in low head bulb turbines intakes [3]. To keep the head loss at the minimum, the non-invasive velocity would be the optimal solution. The ultrasound transit-time or ultrasound doppler profiling systems are hard to implement due to lack of space [4]. Also, there is an option to use scintillation method [5] if conditions for proper operation could be satisfied. In most cases, the "old-school" solution is to use the current meters installed on one (or two) horizontal beam(s) on movable frame and traverse the frame through the whole cross section. Special care is needed to use adequate current meters, self-compensated for angles of incidence that are expected (and checked in advance using CFD, if possible) at measuring profile [1]. It is assumed that reverse flow is not to be measured if current meters are used.

This paper presents the methodology used to measure the flow at inlets of bulb turbines of Hydro Power Plant (HPP) Iron Gate 2 (in Serbian, Djerdap 2). The geometry and disposition of HPP is such that river flow is not perpendicular to inlets, with the inflow angle varying with operating conditions. Since the existing Winter-Kennedy (WK) type flow meter is based on flow coefficients obtained from model, verification measurements were planned to check the influence of HPP's disposition on the WK's uncertainty. However, the operator of HPP hadn't allowed to perform the measurements using stoplog gate slots, downstream the trash racks, so measurements were to be conducted in front of trash rack, where flow conditions are much worse. Instead of mechanical current meters, the 3D Electromagnetic (EM) probes were developed, with the possibility to measure even the reverse flow. Probes were installed on the measuring frame, which was traversed in incremental mode. The existing WK at turbine under the measurement was used to compensate for small inflow instabilities. The continuous mode of traversing was tested too. The tailored software for on-line measurement and off-line data processing, including the uncertainty assessment and report generation, was developed.

2. Hydro Power Plant (HPP) Iron Gate 2 and flow measurement

The Hydro Power Plant (HPP) Iron Gate 2 is situated on a Danube River (44^0 18' 24.61" N, 22^0 33' 53.54" E) between Serbia and Romania (Figure 1) and is operational from 1985. The HPP is equipped with 10 Serbian and 10 Romanian turbines, horizontal Kaplan low head (2.5 – 12.5 m) bulb type (Figure 2), each having 27 MW and flow rates up to 420 m^3/s. Due to HPP's disposition, the lateral inflow velocity V_Y (Figure 2) is not negligeable as was assumed during the turbine's model tests conducted by manufacturer. The additional physical model experiments done during 2005-2006 [1] proved that depending on the operating conditions, inflow angle and can be up to 40^0.

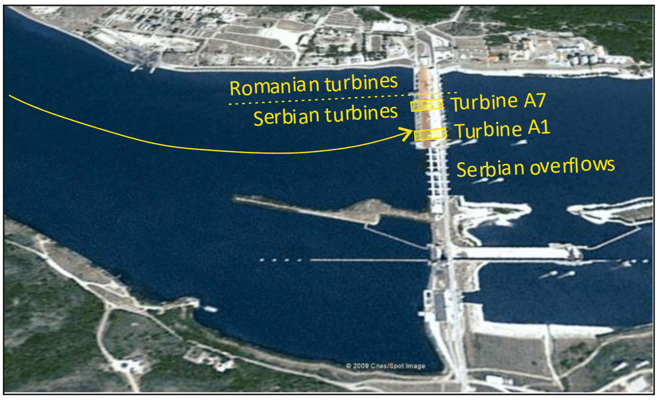

Figure 1: Iron Gate 2 (or Djerdap 2) hydropower plant, 44^{0}18'24.61" N / 22^{0}33'53.54" E (Google Earth, 2009).

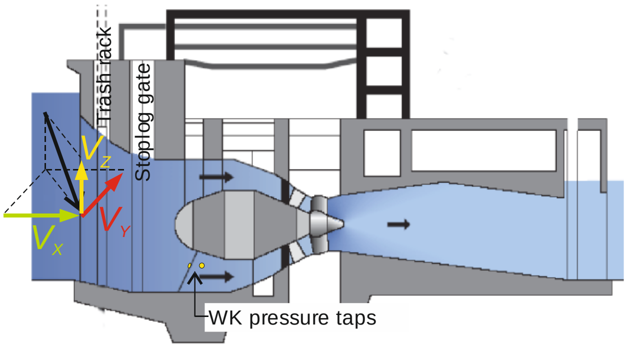

Figure 2: Bulb turbine with highly irregular conditions for proper flow measurement.

The flow rate on each turbine is measured using the WK method. The pressure taps are located on lower, supporting wall (Figure 2). Since the incident water flow direction is not parallel to the turbines, it is legitimate to raise the question of used WK's flow measurement method accuracy. As a part of the turbine revitalization plans, the verification measurements were organized to check the WK's accuracy. The HPP operator has purchased the system (equipment, software, and education) which can be used on all 10 Serbian's turbines. The main limitation was that measuring has to be done without any disturbances to regular turbine's operation, meaning that stoplog gate's slot cannot be used for the measurement and that equipment has to be installed outside the turbine, in front of existing trash rack.

3. Methodology for flow measurement at turbine inlet

The IEC 60041 [2] is not directly applicable to conditions at HPP. The methodology for measurement of bi-directional, full spatial velocity field at the entrance of the turbine was needed, to better understand the flow regime at entrances of HPP's turbines. The comprehensive examination with field tests of different methods was done [4], concluding that the electromagnetic (EM) probes, capable of measurement of all three velocity components (3D) bi-directionally, mounted on movable frame is the best solution. Together with the company Svet Instrumenata [6], the new 3D EM probe was developed (Figure 3). The diameter of probe's head is 65 mm, with the measuring zone diameter approx. 120 mm. Having more than one magnet coil in the spherical head, and several electrodes, the probe can measure X, Y and Z components of the velocity (Figure 3) with standard uncertainty of 0.5% (expanded is 1 %) and minimal velocity of 1 cm/s. Since probe's body influences the velocity field, the calibration chart is not ideal as for 2D probe and has to be established for each supporting frame. The calibration of angular sensitivity is not as easy task as it might look, so the overall accuracy will depend on the effort involved (in this work the calibration uncertainty for single EM is 0.5 %).

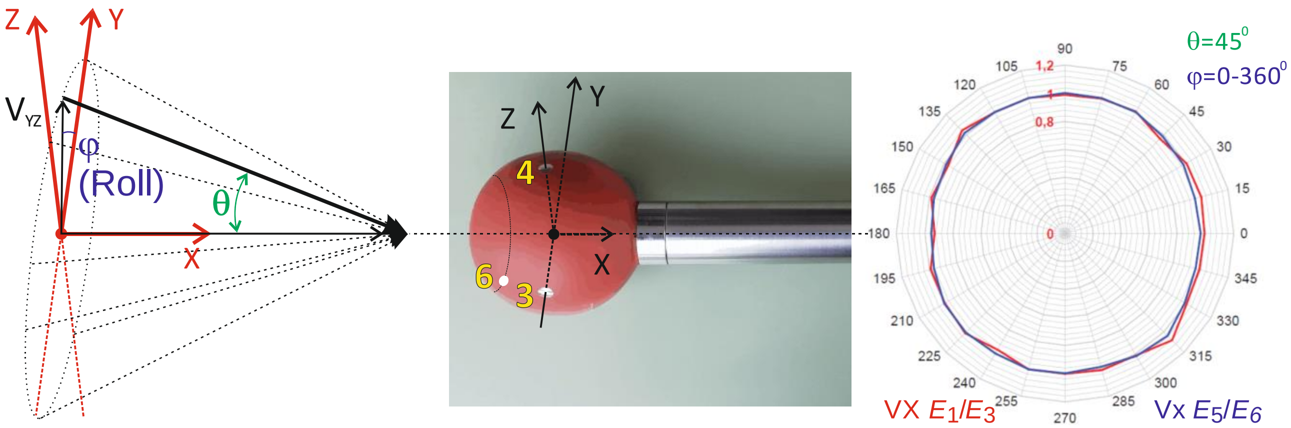

Figure 3: 3D+EM probe with normalized roll (φ) angular sensitivity for two streamwise components VX and Vx for constant incident angle of θ=45^0.

To improve the probe's operation, the most important streamwise (X) component on the EM probe (Figure 3) needed for flow calculation is measured at two positions along the sphere. At the upstream part of probe's head, under the angle of $\theta=45^0$, electrodes E_5 (on opposite side of probe's head, shown in Figure 3) and E_6 are directly measuring the velocity in boundary layer close to the true streamwise velocity (named Vx). This velocity is valid only for unidirectional flow and for small incident angles. At the same time, at standard radial position (angle $\theta=90^0$) the electrodes E_1 and E_3, and E_2 and E_4 (electrodes E_1 and E_2 on opposite side of probe's head) are measuring the averaged streamwise component VX, calibrated for all incident angles, including reverse flows. Thus, the probe will output two signals for streamwise velocity component (that is why the probe is named 3+D type). The standard VX is used to compute the flowrate, and to find the incident angles since it better averages the streamwise component, and Vx is used as control only for smaller incident angles.

The 15 3+D EMs were used to measure the velocity distribution in one profile. Probes were mounted on the lower horizontal bar of the movable 14.5x3.1 m steel frame, shaped to minimize flow disturbances. The frame was installed upstream of the trash rack and was traversed vertically through the whole inflow flow cross section 14.5x26 m (Figure 4). Detail of 3+D EM probe, installed on horizontal bar, is presented on Figure 5.

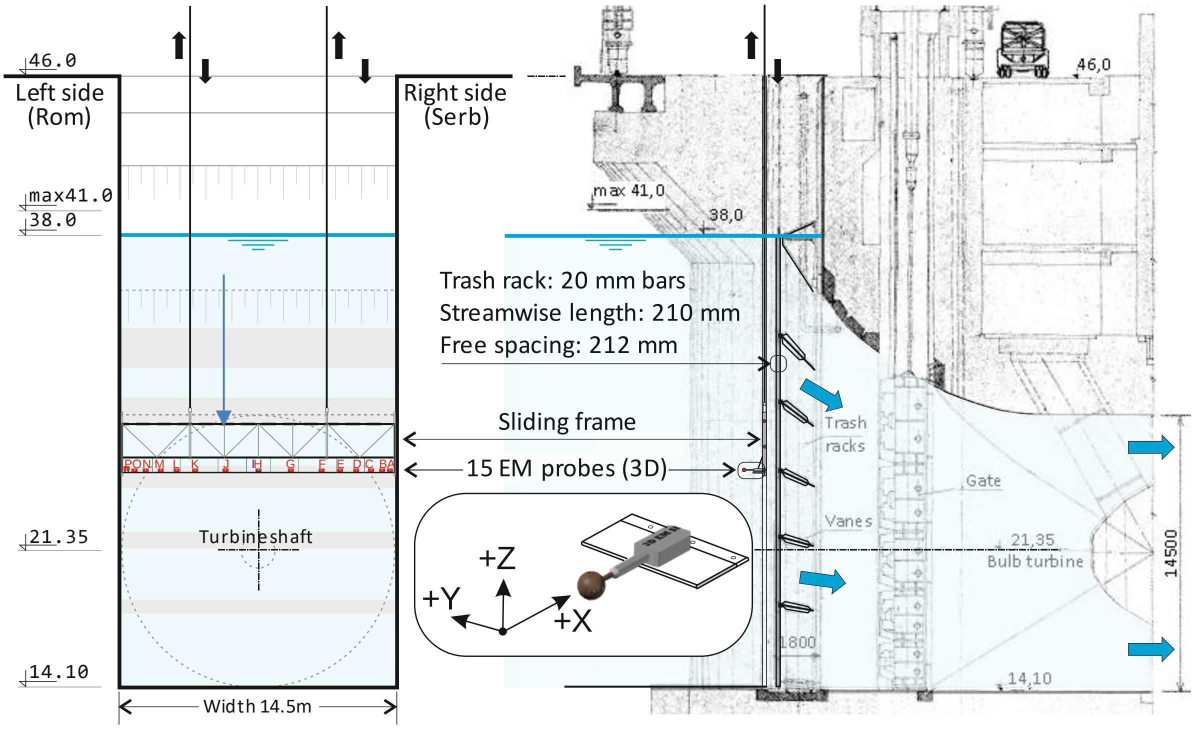

Figure 4: Suggested flow measurement method by profiling velocity field using one row of 3D EM probes - Streamwise view at the turbine's inlet (left side) and longitudinal section through the bulb turbine (right side).

Redundant velocity measurement was done using 2 ADVs ("Vector" by Nortek). To enhance the reliability of redundant measurement, the ADVs were not connected in the on-line measurement system. The local data storage was used, using 1 s data acquisition rate. After one or two days of measurement, data were collected and compared to EM measurements. All 3+D EMs and ADVs were calibrated in towing tank, with supports having the same geometry as used steel frame.

Figure 6 presents the used measurement rig. It comprises of the 15 3+D EMs (each probe measuring 4 velocity components, two angles, real time, and battery status), 2 water level pressure transducers and 2 steel frame's position transducers (with distance travelled and current speed) connected into the measurement network. The RS485 with MODBUS protocol was used. The system was designed to work with 1 s data acquisition rate, but due to the limitations of used PC Windows, the achieved reliable acquisition rate was 2 s. The whole system was powered through the RS485 cable, but each probe had also its own battery as the redundant source.

The measurement methodology also includes the sonar check of the intake's bottom before the velocity profiling. Using 4 sonars installed at the lower horizontal frame's bar (not show on Figure 6), and lowering the frame close to the intake's bottom, the true flow area was checked. Also, the acceleration sensor is added to check the performance of the steel frame during the operation with the maximal flow rate and potential influence on EM probes.

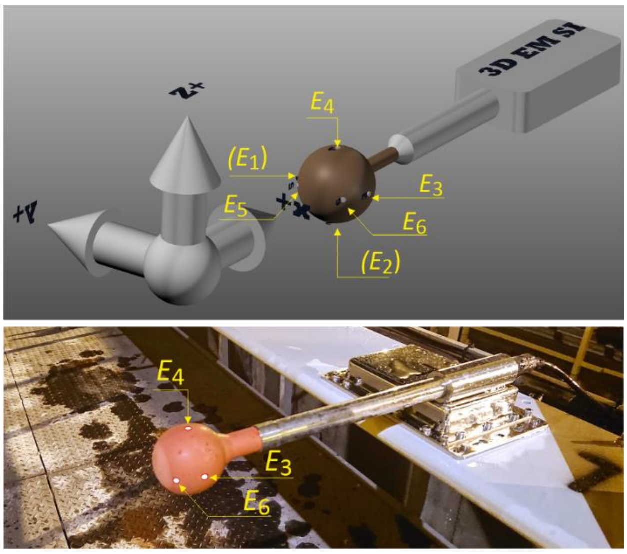

Figure 5: 3+D EM probe schematic drawing and installed on steel frame.

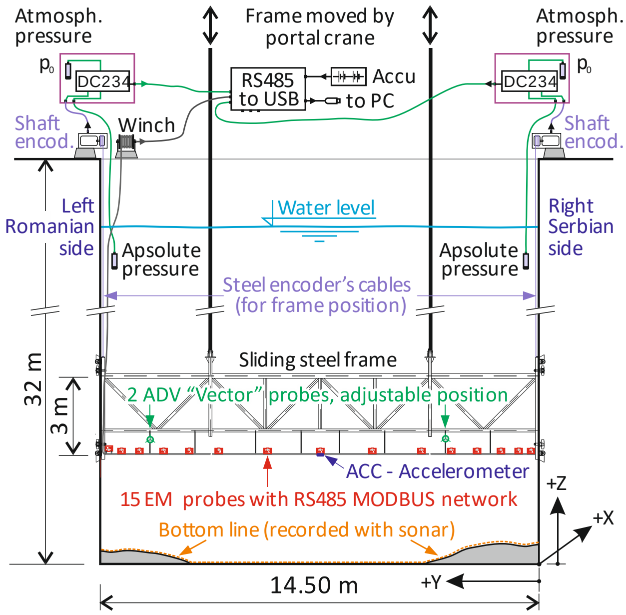

Figure 6: Measurement rig.

Two measurement strategies were possible, incremental, and continuous. In incremental mode, the steel frame was raised from the bottom (average depth of 26 m) in increments between 1.0 and 1.5 m and kept for at least 10 min in fixed position. The averaging time was firstly tested monitoring the flow rate (Figure 7). In the "constant power mode" the slow flow rate oscillations were visible. The 10 minutes was accepted as optimal averaging time. With approx. 18 profiles, the duration of one profiling lasted about 4 hours (Figure 8). In continuous mode the steel frame was traversed through the whole flow cross-section with a constant speed of 0.05 m/s (due to limitation of portal crane, continuous measurement is possible only in upward direction) and measurement lasted about 9 minutes. Although continuous mode is favourable because it allows fast measurement, it was not considered as reliable one: for each vertical profile only 260 samples are acquired, or about 130-150 samples in the area with the higher velocities, which might not be enough to reduce the influence of turbine's flow rate instability. Because of that, the computed flow rate uncertainty is much higher than in incremental mode.

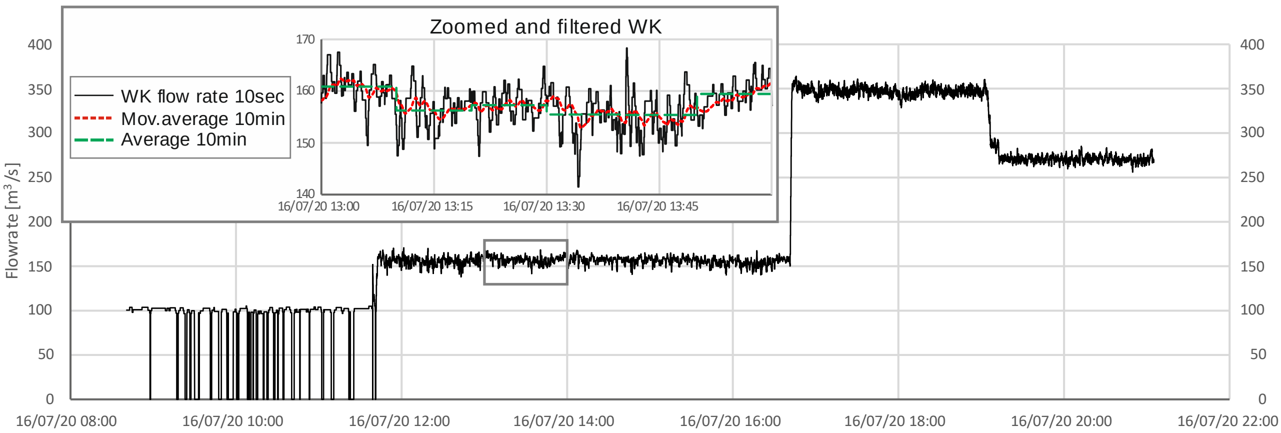

Figure 7: Fluctuation of flow rate measured by WK

Custom made software was designed, which supports the on-line and off-line operation. During the measurement campaign, the on-line data from MODBUS network are directly visible (Figure 8) and stored on the PC. Both incremental with automatic detection of the profiles and continuous modes of operation are possible. In the off-line, or post processing operation, data from different sources are firstly merged (data collected from MODBUS network, data from HPP's operational SCADA with turbine's parameters, and data from ADVs), filtered, tested for stability, compared redundant data, inspected for different errors (Figure 9).

Since the incremental profiling mode can last 4 hours for one flow rate, although the turbine is in constant power mode, the flow rate can fluctuate (Figure 7). In off-line data processing mode, the user can check the overall flow rate stability during the measurement period by plotting the turbine's WK data. Selecting the "representative" time frame, or referent profile (Figure 10, red box at profile no. 5), the average WK flowrate will be used as if that flowrate was constant through whole measurement period [3]. All measured data are linearly corrected: for WK flow rates smaller than representative one (for example, profile no. 3) the measured velocities are increased and vice versa.

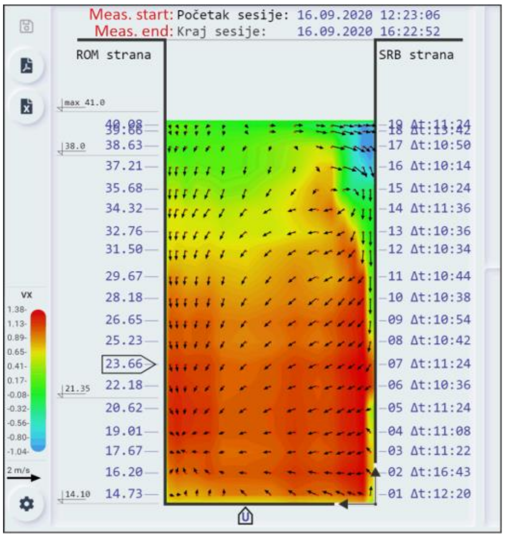

Figure 8: Typical velocity field during measurement (streamwise component colour coded, Y and Z components drawn by the vector, scales are in the lower left corner).

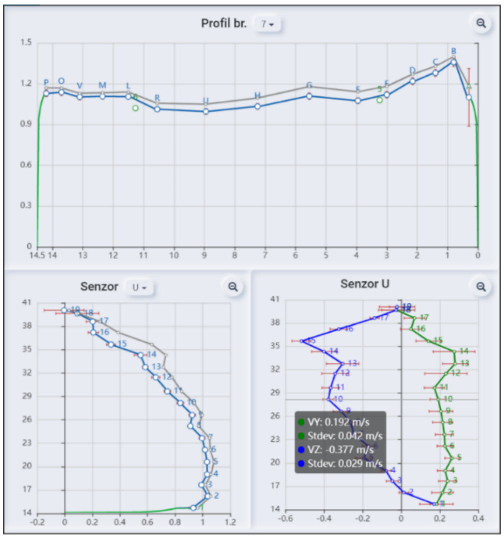

Figure 9: Velocity components with standard deviations: Streamwise velocity in horizontal cross section 7 (upper diagram) and selected components of velocity at vertical cross section U (lower diagrams).

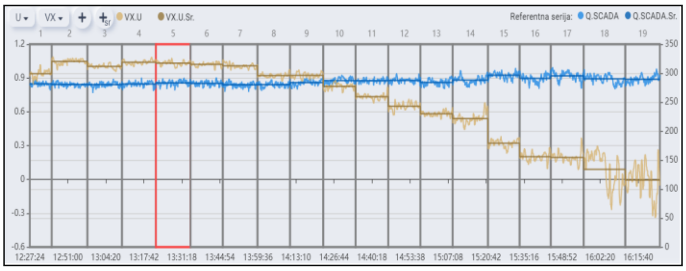

Figure 10: Selection of referent profile.

The streamwise velocity component is linearly interpolated between probes in horizontal plane and then vertically. The velocities in the area where no measurement was performed, peripheral flow area (toward the bottom, left and right walls and surface) are extrapolated using user-selected laws and coefficients with visual check. The calculated flow rate through measured and unmeasured (extrapolated) areas is continuously presented to user. Finally, full uncertainty analysis is performed, and all components are displayed. Also, the turbine's report sheet is produced, comparing WK-referent flow rate with measured flow rate, computed measurement uncertainty and graphical presentation of streamwise velocity.

4. Results of velocity field measurements on two inlets

During the 2020, measurement system was used on the two turbines [5]. The velocity profile was measured using incremental methodology, with profiles between 1.0 and 1.5 m apart, each profile recorded for at least 10 min. Overall measurement time for one flowrate was 4 hours. The continuous mode with traversed speed of 0.05 m/s was also tested but the total uncertainty was too big (between 1.5 % to 4.6 %).

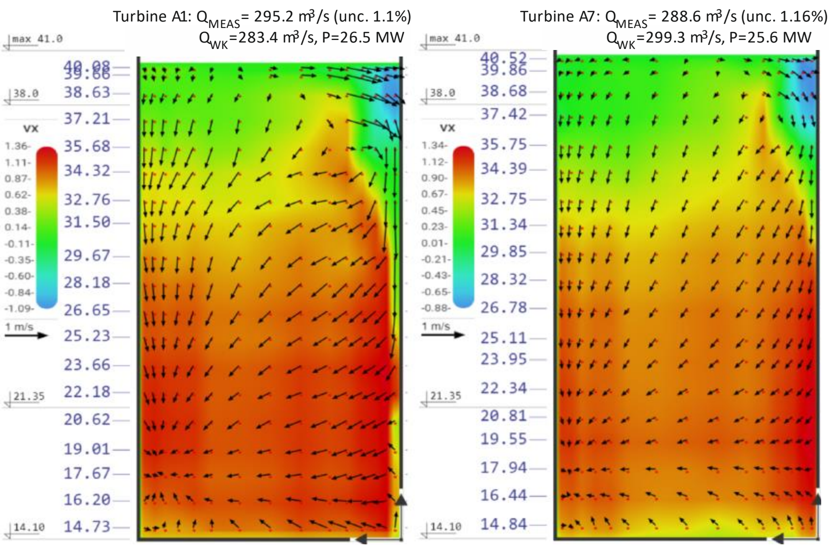

Figure 11: Velocity field for nominal inflow at A1 and A7 turbines.

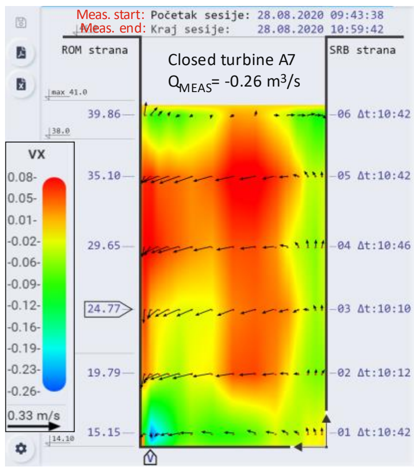

Figure 12: Closed turbine A7, measured velocity filed.

Figure 11 compares the velocity fields for maximal flow rate, for two turbines: A1 which is close to overflow gates (Figure 1) and A7. The streamwise component is presented with colours, and two lateral components with arrows. Obtained results showed that A1 is more influenced by lateral velocity component V_Y than A7, which is consistent with the physical model experiments [1] and operator's experience. The clear swirl is visible at the inlet with reverse V_X velocity in upper region. The calculated flowrate for nominal power was 4 % larger at turbine A1 and 3.7 % smaller at A7, than measured flowrate with WK. Similar results were obtained for smaller turbine powers.

To test the possibility of equipment to measure the small velocities, the profiling of input velocities during closed turbine A7 was performed (Figure 12). Only six horizontal profiles were used. The calculated flow was -0.26 m^3/s, which is smaller than 0.1 % of nominal flow rate.

5. Uncertainty

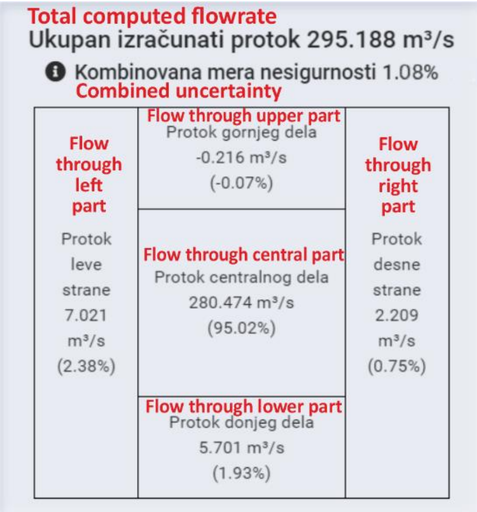

Figure 13: Total flowrate and components of uncertainty

Integral part of total flow calculation is the assessment of uncertainty components. The procedure is developed according to GUM [9] and all components are clearly presented to the user. As expected, the combined uncertainty is low (1.08 % in presented measurement, Figure 13) for incremental type profiling lasting 4 hours, when turbine operation is held (almost) constant. Continuous profiling of same turbine gave the uncertainty of final calculated flow much higher, from 1.5 % to 1.9 %.

6. Conclusion

Presented system allows the inflow measurement in nonstandard conditions, without stopping the turbine or some additional works on removal of hydraulic pre-turbine gate. The overall uncertainty depends on the used number of horizontal profiles and stability of inflow. Achieved uncertainty in two test cases was just over 1 %.

Main drawback of conducted measurements was slow procedure in incremental mode. For 10 minutes averaging per profile about 4 hours for one constant flowrate is needed (Figure 10). Since turbines were in constant power mode during the measurement, there is a chance that the flowrate oscillation was higher than 1.5 % due to automatic correction of turbine's operation mode. There are plans to test the stability of flowrate if the turbine is switched to semi-automatic mode, with fixed guide and runner vanes' position, and with the fixed operation of the two neighbouring turbines. Although the measuring system is prepared to work also in continuous mode, the speed of existing crane was too large, giving higher uncertainties of computed flowrate. However, in planned future measurements this mode of operation will be investigated more thoroughly.

The obtained velocity field is, as expected, strongly influenced by the lateral velocity depending on the turbine position. Downstream the measured section, water passes the trash rack with bars having the L/W ratio close to 1.0 (Figure 4). Unfortunately, it was not allowed to place the measuring equipment downstream the trash rack. It can only be assumed that the lateral velocity is largely reduced and that fine turbulency generated by trash rack helps to improve the irregular inflow velocity profile. However, the irregular velocity field surely increase the losses on the trash rack.

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