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Discharge measurement and performance tests of hydraulic units in low-head small hydropower installations

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Abstract

In course of over half a century the test teams of the Szewalski Institute of Fluid-Flow Machinery (IMP PAN) have conducted numerous performance tests of small hydropower (SHP) installations on various occasions and motivations, including updating or establishing performance characteristics of old machines, acceptance of new units, checking or optimising the cam correlation of new or refurbished double-regulated turbines, checking performance of prototype turbines under field conditions. The discharge measurement techniques have included current-meter, pressure-time and acoustic methods. Index tests, using the Winter-Kennedy and other differential pressure methods, as well as current-meter and acoustic techniques, have been employed quite frequently to optimise the cam curves of double-regulated machines. In one case a simplified technique based solely on the power/wicket gate opening relationship was checked. This paper discusses some techniques applied when determining the absolute efficiency and optimising cam correlations by means of absolute and index test methods. Cubic spline formulae as applied to integrate the flow velocity field in a hydrometric section are derived. Results of a discharge measurement by means of the current-meter and pressure-time method are compared as a special case study. Finally, practical recommendations addressed both to the power plant owners and the test team members are formulated.

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1 Introduction

There are various reasons and motivations to test hydraulic units under field conditions. These include commissioning of a new or rehabilitated unit, optimisation of the power plant operation, detection of the reasons for observed deficiencies, decision on possible overhaul or upgrading, as well as assessment of the investment result, by checking fulfilment of the guarantees declared [1].

While small hydro is often considered a very special component of the hydropower industry, the division between small and large installations is not quite clear. The possibility to use equipment of standardised or simplified design is considered sometimes an important technical criterion [2].

On the other hand, the need for public support or state preferences at some stage of installation development or even operation may be used to establish the installed power, P, limit. In practice the limits between 2 and 50 MW are used over the world with that of $P = 10$ MW prevailing in most European statistics and that of $P = 15$ MW present in the IEC 62006 code on acceptance tests of small hydroelectric installations [3]. Also division between the low and medium head installations is a matter of stipulation. While the head limit of $H = 30$ m may be still used in some parts of the world, the limit of $H = 15$ m is quite typical for lowland countries, especially those developing their small hydro sector [4]. Till mid 80's of the previous century hydraulic turbines were scarcely operated at heads below 2.5 m. Since then this limit has been shifted by about 1 m downwards. The heads below 2.5 or even 4 m are often named very low or ultra low ones.

Due to relatively high costs, the scope of acceptance and commissioning tests in small hydropower installations is generally much lesser than that in the larger plants. Typically, all safety tests (including start-up, steady-state run, normal and emergency shut downs including load rejection) as well as a trial run and runaway safeguard reliability tests are conducted. Optimising the cam correlation of double-regulated machines is generally performed as well. Index tests aimed at checking the shape of power characteristics are often recommended for medium-size units. However, comprehensive performance tests, including determination of absolute efficiency, are usually required only in case of new designs or relatively large units (several MW output). This viewpoint is well reflected by the abovementioned IEC 62006 code, which distinguishes between 3 classes of acceptance tests (Tab. 1).

Table 1: Performance characeristics depending on the test class (IEC 62006).

Class	General pescription	Performance characteristics determined	Commnets
A	Normal test	Maximum power output	Default
B	Extended test	Maximum power + performance curve shapes (index test)	Reccomended
C	Comprehensive test	Absolute values (including efficiency)	Optional

For B and C classes discharge measurement is quite essential. Whereas index test is sufficient for class B, the absolute discharge value has to be determined in case of class C. In fact, class C requirements are equivalent to those of the IEC 60041 code [5] . Due to several reasons, this poses quite a challenge in case of numerous low-head installations.

It is generally known that the optimum cam dependence of the prototype double-regulated machine may deviate by some 10% of the wicket gate opening range from that established basing on model tests and/or computational fluid dynamics (CFD) calculation. Additionally, partial load and overload dynamic phenomena may affect the final shape of the cam characteristics. These effects can be hardly modeled with sufficient accuracy, especially in case of the run-of-river installations, featured by strong head/discharge correlation. Therefore it is recommended to revise and update the design dependences basing on site test results. The difficulties arise in case no discharge measurement is planned (class A tests). Some suppliers use solely the power/wicket gate opening correlation in such circumstances. The other option is to use the vibration measurement data. Both methods are of limited accuracy. However, in case of severe deviation between the design and the actual head and/or justified suspicion that the optimum cam curve might differ from the design one by more than 10% of the maximum wicket gate opening, it may be reasonable to apply them for temporary setting of the cam correlation.

2 Discharge measurment

2.1 General

Direct measurements of absolute discharge are a prerequisite for comprehensive tests in most hydropower installations. In case of the lowest heads, applying velocity area methods for this purpose is the only choice. Local velocity can be determined using various instruments, including current-meters, electromagnetic meters, Pitot tubes. Ultrasonic scanning of the measurement section is becoming an ever more attractive technique, but high costs and sensitivity to flow disturbances still prevent its wide implementation. As the use of Pitot tubes is cumbersome and restricted to some special applications and electromagnetic meters are used mainly for hydrological purposes, propeller current-meters remain still the most popular instrument for determining local velocity during performance tests.

Pressure-time and acoustic methods are applicable in schemes with sufficiently long diversion conduits. This feature excludes the lowest head installations. Furthermore, in numerous cases no access from outside of the conduit exists and internally mounted pressure taps and transducers have to be applied. Transit-time acoustic methods are rarely used for comprehensive tests in small hydropower installations. Reliable measurement requires multi-path stationary system, usually considered an unjustified expenditure in a small scheme. Portable systems (both Doppler and transit-time) are used mainly for index test purposes and for measurements of lesser accuracy requirements.

2.2 Current-meter technique

Proper conditions for current-meter measurements are generally encountered in diversion schemes with penstocks of sufficient length and diameter, allowing for installation of a supporting cross. Measurement under such conditions may be very accurate provided current-meters are properly distributed and the blockage effect is duly taken into consideration. Measurement in a diversion channel may be also very accurate although installation of a stationary supporting framework may be problematic in this case.

If necessary infrastructure exists or can be erected, the manually handled vertical supports (current-meter rods) are often the best choice. The disadvantage of this technique is relatively long time needed for each test run. This can be substantially shortened if several rods are used at the same time. In case of sufficient number of available current-meters, fixing the rods at selected positions is highly recommended. This is especially practical in case of index tests when using as little as 3 measurement verticals may appear sufficient to determine properly the shape of efficiency characteristics of the unit.

In most Polish low head schemes discharge measurements have to be conducted at water intakes (mainly in stoplog hollows), in short intake waterways or directly in the turbine chamber as this has been shown in the first two photographs of Fig. 1. In some old type power plants, especially those with long tail races and vertical draft tube Francis turbines, measurement in a tail race section may

Figure 1: Current-meter measurements at the intake, in the turbine chamber and at the tailrace in Borowo ($P = 2 \times 450$ kW, $H = 8.10$ m), Owidz ($P = 245$ kW, $H = 3.50$ m) and Niedalino ($P = 3 \times 350$ kW, $H = 9.25$ m) SHPs, respectively.

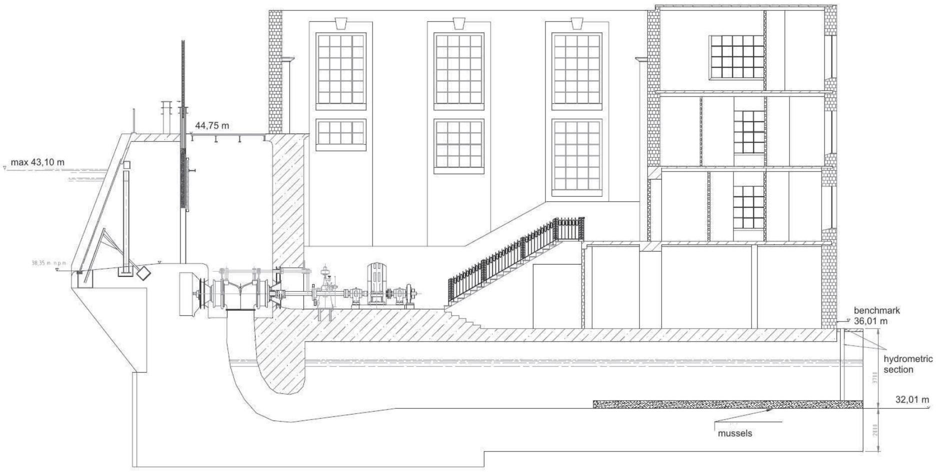

Figure 2: Location of the hydrometric section at the end of a long outlet channel in Niedalino SHP (courtesy: Energa Wytwarzanie Sp. z o.o.).

appear also reasonable (see Fig. 2 and the last photograph of Fig. 1). The main difficulty in all cases mentioned is nonuniformity in spatial and temporal distribution of the velocity vector orientation. The general remedy is using component current-meters capable to measure properly axial velocity component in case of velocity direction deviating from that of the propeller axis by up to 45 °C. If the measurement is conducted at the intake structure and the component current-meters are not available or the flow is featured by large scale eddies, the IEC 60041 code recommends extending the intake by a bell-mouth structure erected at the head race side. Another option, applicable also for measurement in short waterways and at the turbine chamber inlet, is orienting current-meters along streamlines as determined by means of the CFD technique. Velocity component normal to the measurement section plane can be easily calculated using direction coefficients. This approach has been used by the IMP PAN team on numerous occasions. Great care and proper experience in interpreting calculation results are always recommended as the following factors are to be accounted for:

1) sensitivity of streamline pattern calculation to the assumed boundary conditions;
2) difficulties in assessing uncertainty due to the CFD calculation and to the errors in current meter positioning – especially in case of irregular and/or fluctuating flow patterns.

The lowest uncertainty may be expected in case of measurement sections located in sufficiently long and regularly inclined waterways.

In case of substantial water depth and/or high flow velocities, the manually handled vertical supporting rods of small diameter (typically 20 mm) may be replaced by some light pipes featured by rectangular cross-section and relatively high stiffness. Guys applied when changing positioning of the current-meter supporting components proved highly efficient on several occasions.

If horizontal supporting frames and stationary frameworks are constructed using commercial pipe segments, simple analytic formulae for velocity field components of perfect liquid flowing past a circle may be applied in order to establish the proper positioning of the current-meter respective the supporting pipe segment [1]. The criterion used in the IMP PAN team practice is velocity disturbance in axial direction not higher than 0.2%. The streamline orientation disturbance is kept below $5\,^{\circ}$C. In case of a moving frame this implies that the axial and transversal distances of the propeller reference point from the supporting pipe centreline – x and z, respectively – should be equal each to other and not lower than 2.5 pipe diameters. The last requirement enables avoiding the areas of highly nonuniform velocity field (Fig. 3). If the current-meters are to be situated directly or almost directly beneath the supporting pipe (very narrow stoplog hollows) the distance of even 10 diameters may be needed (Fig. 4) [6]. The last mentioned distance is recommended also in case of the current meter axis forming common plane with the pipe centreline (typical for supporting crosses and stationary frameworks). The interception point of current-meter axis with transversal plane adjacent to

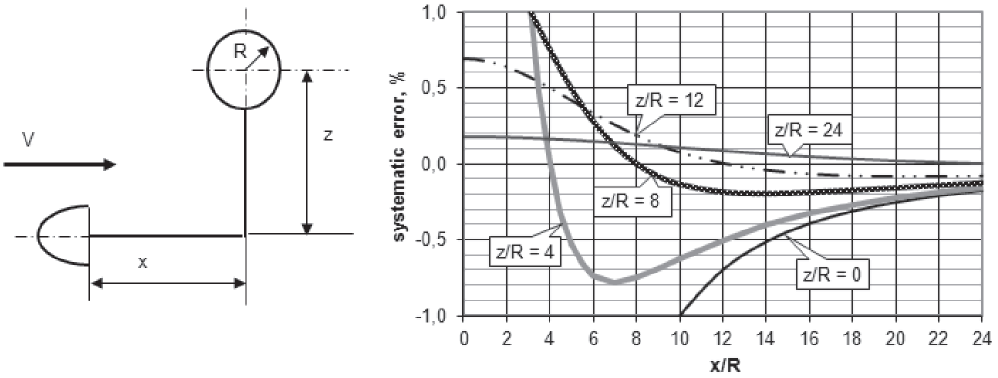

Figure 3: Systematic error in current-meter measurement due to the supporting rod influence as dependent on the current-meter position in respect to the rod centreline.

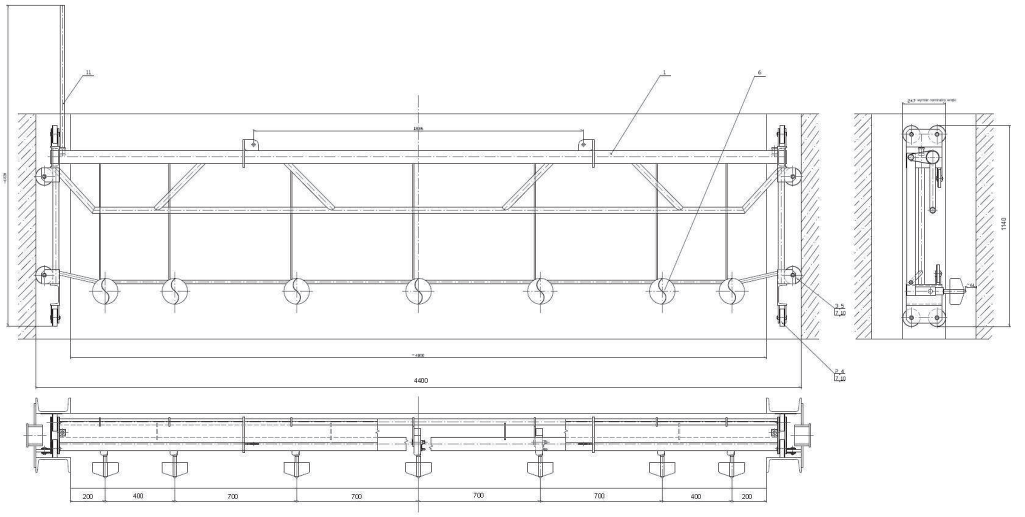

Figure 4: Excerpt of an assembly drawing of the current meter supporting frame as applied at one of 3 hydrometric sections in Laczany SHP ($P = 2350$ kW, $H = 5.4$ m) [6].

the propeller trailing edges is used as the reference point in this consideration. The compromise between high stiffness of the supporting structure and low velocity field disturbance is achieved by applying streamlined profiles constructed out of two parallel pipes of different diameter. The aforementioned procedure of determining current-meter positioning provides safe results as it is based on the ideal liquid calculation upstream of the pipe section. Lower distances may be applied if justified by CFD calculation with realistic supporting structure profile and the Reynolds number accounted for.

In case of supporting frames traversing the hydrometric section, every effort is done to hide the rollers in the roller hollows. Due to unknown velocity profiles close to the measurement section bottom and top edges, the integral technique (with continuously moving frame) is used solely for the cam optimization purposes. Keeping the frame at some still position in the mid of the measurement section may save time and provide results sufficient for establishing the optimized cam dependence. However, the shape of the optimized efficiency curve may get distorted due to the possible mainstream shift in the vertical direction. The shift in the horizontal direction is usually much more significant and therefore using less than 3 vertical supporting rods as kept in stationary position has been found undesirable for the purpose of index tests.

Due to friction forces in the bearings and some other reasons there exists a hyperbolic relationship between the local flow velocity and the propeller rotation speed [7, 8]. For sufficiently high velocities this can be approximated by means of a linear equation. Rotation speed is usually determined by counting the number of electrical pulses generated at each revolution of the current meter propeller. Previous electromechanical arrangements, used by the IMP PAN team till mid nineties, have been replaced step-by-step by reed relays. The relays close and open the electrical circuit in response to the change in magnetic field flux, as induced by a permanent magnet rotating with the propeller shaft. Over the last half century the pulse counting technique has been subject to numerous changes and revisions. Today the IMP PAN test team uses the *IOTech* and *National Instruments* data acquisition boards for this purpose. The DASYLab[1] software is used to identify individual pulses (Fig. 5) from the high frequency sequence of samples. Two independent algorithms are used for detecting possible distortion of the original signal. In addition to the basic file with the terminal number of pulses, a file containing a sequence of interim records is created. This feature allows to use the data recorded even in case of failure in the final stage of the test run (e.g., human error or unexpected emergency shut-down). The other advantage is possibility to evaluate the low frequency velocity fluctuations and related uncertainty in local velocity measurement. Online monitoring of the number of pulses counted by individual current-meters enables detection of any serious malfunction in the counting process. In case of movable current-meter supporting structures, the proper action may be implemented during the measurement, in-

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[1] DASYLab is a registered trademark of National Instruments.

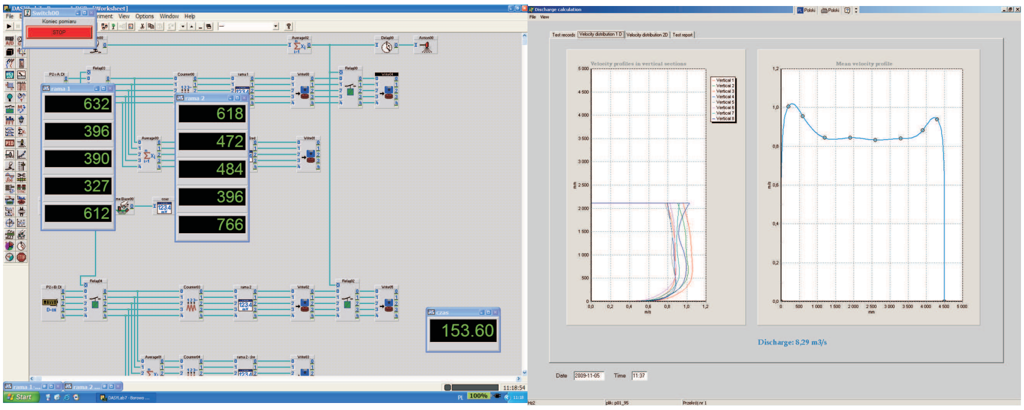

Figure 5: Counting of current-meter pulses by means of the DASYLAB software and determination of velocity profiles (FLOWTEST proprietary code) at the intake of a low head SHP. Copies of computer screens taken during data acquisition and discharge calculation, respectively.

cluding checking and/or replacement of the relevant current-meter.

An abundant literature on the velocity field integration methods is available, just to mention the classic hydrometry monograph of A.T. Troskolanski [8], VDI recommendations [9] and ISO standards [10, 11]. Due to enormous progress in computational technology, graphical and arithmetic techniques have been practically replaced by various numerical schemes. In addition to those recommended by the ISO 3354 standard, it is worthwhile to mention the schemes based on spline techniques, including those developed by the German Power Plant Union (VDEW) working-team 'Measurement methods in hydropower engineering' [12, 13]. The general advantage of the spline approach is the resulting capability to visualise the velocity distribution profiles. This is of great significance if possible malfunction of any current-meter or inadequate positioning/number of measurement levels and/or verticals is to be stated just after the test run or during detailed data analysis. Also at this stage relevant action can be taken sometimes, contributing thus to high reliability of the test results.

All spline techniques assume some smoothness conditions at the nodes between interpolated segments. The classic condition of velocity profile smoothness up to the second derivative is used in references [14,15]. The VDEW technique replaces the requirement of the second derivative smoothness with additional conditions imposed on the first derivatives which make the whole procedure less sensitive to uncertainty in current-meter positioning.

Another important aspect is proper modeling of velocity profile close to the walls and the free surface. Using the classic von Kármán law between the stiff wall and the first current-meter as-sumes implicitly the current-meter to be positioned exactly at the boundary layer edge which is generally not true. At the same time an unrealistic boundary condition may be imposed on the main flow profile in the peripheral current-meter vicinity. This drawback is avoided in the IMP PAN cubic spline approach by using the power-linear velocity profile

$$v(x) = mAx^{1/m} + Bx\,, \tag{1}$$

with A, B – constant coefficients to be established from the velocity profile smoothness conditions and x – distance from the streamlined wall. The boundary layer parameter m may may be determined according to the procedure described in ISO 3354. As the procedure assumes a well established boundary layer and the positioning of the first current-meter can be by no means identified with the boundary layer edge, the final decision on the m parameter value is taken only after assessing the whole velocity distribution. The significance of the linear term in Eq. (1) rises gradually with rising distance from the wall. This ensures both adherence to the von Kármán law in the nearest vicinity of the wall and the required flexibility of the formula close to the first current-meter position. Application of a square term in Eq. (1) [15] has been finally abandoned after finding that this often lead to unjustified waviness in velocity profiles close to the first interpolation node.

There are scarce recommendations to be found in the literature on proper modeling of velocity profile in the vicinity of a free surface. In the IMP PAN cubic spline approach the linear-log law

$$v(y) = A(y - y_{p-1}) + B \ln \frac{y}{y_{p-1}} + v_{p-1} \tag{2}$$

is used to model velocity profile above the last but one current-meter below the free water surface. The notation used in the above formula is as follows: A, B – constant coefficients to be established from velocity profile conditions in the last two nodes, p – number of current-meters in a single vertical, y – distance from the hydrometric section bottom edge (Fig. 6). It is to be mentioned that the linear-log profiles have been used in the ISO 3354 and 748 standards as a rough general purpose approximations of full velocity profiles when deriving the arithmetic methods. The distance of 200 mm is generally applied between the last two current-meters in order to fulfill the requirements of IEC 60041 in case the upper current-meter is too close to the free surface. In the latest case the pulses generated by the last current-meter may be used only as an indication of the velocity

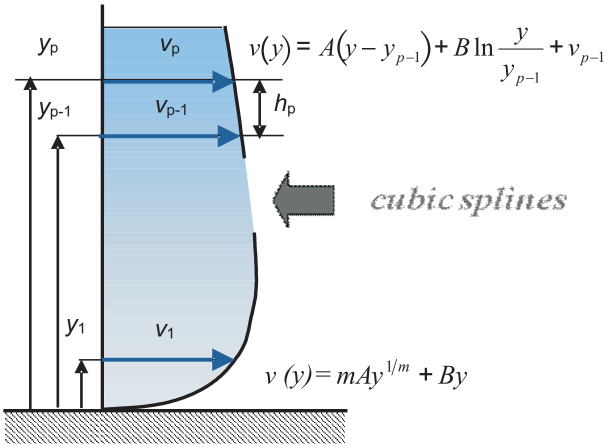

Figure 6: The vertical velocity profile integration scheme in an open channel cross section.

profile trend and not as a valid measurement result. Visual observation of water surface is highly recommended in such circumstances.

In the further part of this section the subscripts $i = 0, 1, \ldots, p, p{+}1$ are used to denote the interpolation nodes situated along the hydrometric section transversal under consideration. While nodes no. $1, \ldots, p$ are located at positions of consecutive current-meters, subscripts 0 and $p{+}1$ are reserved for transversal interception points with hydrometric section edges. No. $p+1$ node exists in case of a vertical transversal in an open channel (Fig. 6).

The requirement of velocity distribution smoothness up to the second derivative in the wall vicinity results in the following set of equations:

$$\begin{cases} mAh_1^{1/m} + Bh_1 = v_1 \\ Ah_1^{1/m} + B = -\frac{h_2}{3}M_1 - \frac{h_2}{6}M_2 + \frac{v_2 - v_1}{h_2} \\ \frac{1-m}{m}Ah_1^{1/m} = M_1 \end{cases} \tag{3}$$

with $h_i = l_i - l_{i-1}$ denoting the distance between consecutive nodes no. i and $i-1$, l_i – the distance of node i from the hydrometric section left or bottom edge and M_i – the second derivative of the interpolation curve in node i. After some transformations the relationship

$$M_1\left(mh_1 + \frac{h_2}{3}\right) + M_2\frac{h_2}{6} = \frac{v_2h_1 - v_1(h_1 + h_2)}{h_1h_2} \tag{4a}$$

between M_1 and M_2 and the formula allowing to determine A and B coefficients can be derived from Eq. (3). The same condition imposed in node p yields

$$M_p\left(mh_{p+1}+\frac{h_p}{3}\right)+M_{p-1}\frac{h_p}{6}=\frac{v_{p-1}h_{p+1}-v_p(h_p+h_{p+1})}{h_ph_{p+1}}\,. \tag{4b}$$

The A and B coefficients in formula (2) can be calculated from the velocity value measured at the last level and the smoothness conditions in node $p-1$:

$$\begin{cases} Ahp+B\ln\frac{y_p}{y_{p-1}}+v_{p-1}=v_p \\ A+\frac{B}{y_{p-1}}=\frac{h_{p-1}}{6}M_{p-2}+\frac{h_{p-1}}{3}M_{p-1}+\frac{v_{p-1}-v_{p-2}}{h_{p-1}} \\ \frac{-B}{y_{p-1}^2}=M_{p-1} \end{cases}. \tag{5}$$

The relationship between the second derivatives at levels $p-2$ and $p-1$ follow from the above as

$$M_{p-1}\left(y_{p-1}-\frac{y_{p-1}^2}{h_p}\ln\frac{y_p}{y_{p-1}}+\frac{h_{p-1}}{3}\right)+\frac{1}{6}M_{p-2}h_{p-1}=\frac{v_p-v_{p-1}}{h_p}-\frac{v_{p-1}-v_{p-2}}{h_{p-1}}\,. \tag{6}$$

The conditions in the intermediate nodes may be written down in the classic form

$$M_{i-1}h_i+2M_i(h_i+h_{i+1})+M_{i+1}h_{i+1}=6\left(\frac{v_{i+1}-v_i}{h_{i+1}}-\frac{v_i-v_{i-1}}{h_i}\right), \tag{7}$$

where i= 1, 2, 3, …, $p-1$ in case of velocity profile confined between solid walls and i= 2, 3, …, $p-2$ in case of a velocity profile with free surface.

The system of linear Eqs. (4) and (7) or Eqs. (4a), (6) and (7) is featured by a triple-diagonal matrix and can be easily solved without using advanced routines. The velocity distribution between nodes $i-1$ and i, follows now as

$$\begin{aligned} v(x)=M_{i-1}\frac{(l_i-x)^3}{6h_i}&+M_i\frac{(x-l_{i-1})^3}{6h_i} \\ &+\left(v_{i-1}-\frac{M_{i-1}h_i^2}{6}\right)\frac{l_i-x}{h_i} \\ &+\left(v_i-\frac{M_ih_i^2}{6}\right)\frac{x-l_{i-1}}{h_i} \end{aligned} \tag{8}$$

with x standing for the current point distance from the left interpolation edge, $i=2,3,\ldots,$ p in case of a velocity profile confined between solid walls and $i=$

$2, 3,\ldots, p-1$ in case of a velocity profile with free surface. In the peripheral zones formulae (1) and (2) apply.

The mean velocity along the vertical or horizontal transversal of a hydrometric section can be calculated now by analytic integration as

$$U = \frac{1}{L}\int_0^L v(x)dx \tag{9}$$

with L standing for the hydrometric section extent as measured along the mentioned transversal.

The contributions from segments between nodes 1 and p or 1 and $p-1$ follow from the above as

$$\Delta U_i = \frac{1}{L}\int_{l_{i-1}}^{l_i} v(x)dx = \frac{h_i}{L}\left[\frac{v_i + v_{i-1}}{2} - (M_i + M_{i-1})\frac{h_i^2}{24}\right] . \tag{10}$$

The contributions from the utmost segments follow by analytic integration of Eqs. (1) and (2) as

$$\Delta U_1 = \frac{1}{L}\int_0^{l_1} v(x)dx = \frac{h_1}{L}\Big(\frac{m^2}{m+1}A_1 h_1^{1/m} + \frac{1}{2}B_1 h_1\Big) , \tag{11a}$$

$$\Delta U_{p+i} = \frac{1}{L}\int_{l_p}^{L} v(x)dx = \frac{h_{p+1}}{L}\Big(\frac{m^2}{m+1}A_p h_{p+1}^{1/m} + \frac{1}{2}B_p h_{p+1}\Big) \tag{11b}$$

and

$$\Delta U_p = \frac{1}{L}\int_{l_{p-1}}^{L} v(y)dy = \frac{1}{L}\Big(A\frac{h_p + h_{p+1}}{2} - B + v_{p-1}\Big)(h_p + h_{p+1}) + B\ln\frac{L}{l_{p-1}} , \tag{12}$$

respectively, with subscripts applied to A and B coefficients in Eq. (11) in order to distinguish between the left and the right edge of the integration interval.

Integration of mean velocities in direction perpendicular to that of the first integration is needed for the purpose of calculating the discharge. In case of a horizontal supporting frame moved in a regular rectangular section the first integration is conducted along the frame and the second one in the vertical direction. This approach is to be abandoned in case of significant irregularities stated at the section bottom edge. In such a case the mean velocities, U, along the vertical transversals are calculated first and the discharge is determined from the integral

$$Q = \int_0^{L_x} L_y(x)U(x)dx , \tag{13}$$

where $L_y(x)$ denotes the section vertical extent as measured at distance x from the left section edge and L_x is the section size in horizontal direction (Fig 7). The same approach is generally adopted in case of stationary frameworks and in case of manually handled vertical rods as applied during measurements in open sections. Mean velocities are generally interpolated using the procedure applied for the first integration purpose. Exceptions include measurements in seminatural open channels with shallow and/or weedy hydrometric section peripheral areas, for which formula (1) can be no more applied. In such a case the classic cubic splines are used up to the very end of the integration interval where a condition of vanishing second derivative is imposed. In case of L_y showing variable value along the integration interval, the Simpson rule procedure [16] is used.

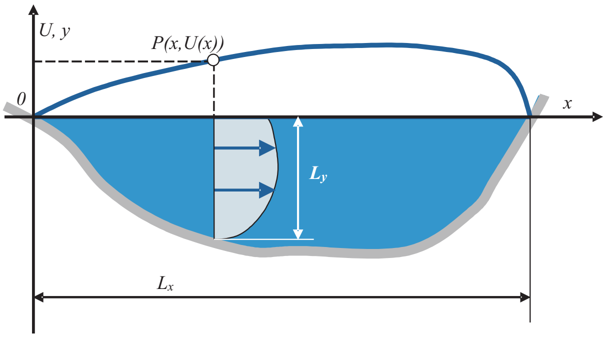

Figure 7: The mean velocity integration scheme in an irregular open channel cross section.

Measurements in closed circular sections are usually conducted using a supporting cross (Fig. 4) and the first integration in the IMP PAN algorithm is performed along the individual arms, according to the formula

$$U(\varphi) = \frac{2}{R^2}\int_0^R v(r,\,\varphi)r dr \tag{14}$$

with R denoting the section radius and $(r,\,\varphi)$ standing for polar coordinates of the actual point.

With current-meters numbered individually for each arm from the cross-section centre to the edge, the contributions from segments $i = 1,\,2,\,\ldots,\,p$ follow as

$$
\begin{aligned}
\Delta U_i = \frac{2}{R^2}\int_{R_{i-1}}^{R_i} v(r,\,\varphi) r dr = \\
= \frac{2}{R^2}\Big[\frac{M_{i-1}-M_i}{45}\Delta R_i^4 - (M_i R_{i-1} + M_{i-1}R_i)\frac{\Delta R_i^3}{24} + \\
+ (v_i - v_{i-1})\frac{\Delta R_i^2}{3} + (R_i v_{i-1} + R_{i-1}v_i)\frac{\Delta R_i}{2}\Big]
\end{aligned}
\tag{15}
$$

with index 0 reserved for the value in the cross-section centre, R_i standing for the ith current meter distance from the cross-section centre, and $\Delta R_i = R_i - R_{i-1}$.

The contribution from the peripheral zone can be calculated now as

$$
\begin{aligned}
\Delta U_{p+1} = \frac{2}{R^2}\int_{R_p}^{R} v(r) r dr = \\
= \frac{2\Delta R}{R}\left[m^2 A \Delta R^{1/m}\Big(\frac{1}{m+1} - \frac{\Delta R/R}{2m+1}\Big) + B\Delta R\Big(\frac{1}{2} - \frac{\Delta R/R}{3}\Big)\right]
\end{aligned}
\tag{16}
$$

with $\Delta R = R - R_p$ standing for the peripheral zone width.

Classic cubic spline algorithm for periodic function interpolation is employed for integration in the circumferential direction. The final formula is as follows:

$$
Q = \frac{R^2}{2}\int_0^{2\pi} U(\varphi) d\varphi = \frac{\pi R^2}{N}\sum_{i=1}^{N}\Big(U_i - \frac{M_{i-1}+M_i}{4}\Delta\varphi^2\Big) \tag{17}
$$

with N denoting the number of arms (typically 4), $\Delta\varphi = 2\pi/N$, U_i, and M_i standing for the velocity averaged along the ith arm and the second derivative of $U = U(\varphi))$ function corresponding to the same arm, respectively. Due to periodicity condition the subscripts 0 and N are equivalent each to other.

In addition to the classic cubic spline technique, the nonuniform rational basis splines (NURBS) [17] have been ever more often used by the IMP PAN test teams in the recent years [18]. Irrespective of the much more sophisticated structure of rational B-splines than that of the cubic ones there is a clear difference in modeling the peripheral zone velocity profile between the methods.

The essential point in the IMP PAN NURBS approach is replacing nodes at the interpolation interval ends (solid walls) by nodes situated at the boundary layer edge. For this purpose the boundary layer thickness is calculated from the formula

$$
\delta_{BL} = \frac{0.37Z}{\mathrm{Re}_Z^{0.2}} \tag{18}
$$

derived for turbulent boundary layer developing at a streamlined flat plate [19]. In case under consideration Z denotes the hydrometric section distance from the water intake while Re_Z is Reynolds number based on the Z value and defined as

$$\mathrm{Re}_Z = \frac{V_{av} Z}{\nu} \tag{19}$$

with V_{av} – average main flow velocity celculated as arithmetic mean of the velocities shown by all curent-meters in the hydrometric section, ν – kinematic viscosity of water.

According to the approach the velocity distribution between the wall and the boundary layer outer edge is described by the von Kármán formula

$$v(x) = V_0 \Big(\frac{x}{\delta_{BL}}\Big)^{1/m} \tag{20}$$

with V_0 denoting the water velocity shown by the current-meter closest to the boundary layer edge. Formula (20) defines also all necessary boundary conditions at the new end of spline inter-polation interval.

Numerous comparative tests on various integration techniques including graphic ones, ISO 3354 numerical scheme, cubic splines, NURBS and even CFD approach (with measurement results taken as boundary condition) show high compatibility, with typical deviation below 0.5% in case of proper measurement conditions, conforming to the ISO 3354 and IEC 60041 requirements. Higher discrepancies may be observed sometimes in case of short intakes, requiring component current-meters.

In case of stationary frameworks in closed conduits the blockage effect has been confirmed as a factor that should never be disregarded. The phenomenon can be explained by the shift of velocity streamlines towards the tip edge of current-meter propellers which results in an increased torque at the shaft. Therefore the authors recommend accounting for the blockage effect both in closed conduits and open channels in case the hydrometric section blockage ratio exceeds 0.2% as specified in the ISO 3354 standard. The IMP PAN team experience shows that the ISO 3354 recommendations on blockage effect calculation provide reliable values for blockage coefficients as high as 2%.

2.3 Current-meter versus pressure-time method

The pressure-time method is based on the first and the second laws of dynamics as applied to the decelerated mass of liquid flowing through a pipeline. The inertia force of the stopped liquid mass is manifested by the pressure difference between two measurement sections in the conduit. The discharge is calculated by integrating the recorded pressure difference curve within the properly determined time interval. The formula applied is

$$Q = \frac{A}{\rho L} \int_{t_0}^{t_k} \left[\Delta p(t) + \rho g \Delta z + P_f(t)\right] dt + q \,, \tag{21}$$

where A is the cross-sectional surface area, ρ – liquid density, L – distance between measurement sections, g – acceleration of gravity, Δp and Δz – the static pressure and centreline elevation difference between sections, P_f – friction force term, q – discharge under terminal conditions (usually the leakage rate through the cut-off device in the closed position).

The method was invented by N. Gibson in the beginning of twenties of the last century [20]. For a long time it was used mainly in US and Canada. Since the advent of computerised data acquisition techniques the method has been ever more frequently used also in Europe. The IMP PAN team has applied it successfully since mid nineties of the last century contributing substantially to increasing its accuracy and applicability range, e.g. [21, 22].

Due to the limited amount of instrumentation needed, the pressure-time (Gibson) method shows sometimes clear advantages when compared with the current-meter technique. However, the method is not quite typical for small low-head schemes as a straight pressure conduit segment of sufficient length is required. This is the case in Zur hydropower plant (HPP); two vertical Kaplan units of 4.3 MW capacity each and 15 m rated head, Fig. 8. Current-meter and pressure-

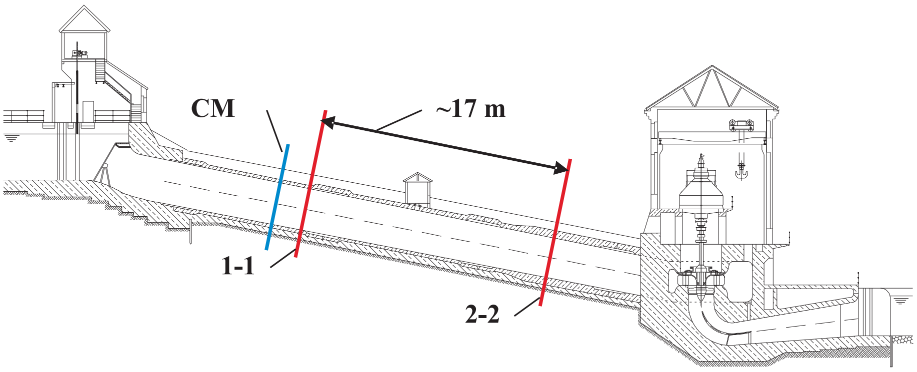

Figure 8: Zur HPP layout with marked hydrometric sections used for the current meter (CM) and Gibson method measurement.

time method were applied simultaneously here to measure discharge at previously optimised operating conditions [23]. Both the supporting cross with 26 current-meters and the pressure-time method instrumentation with hermetic differential pressure transducer were installed inside a penstock of 4 m diameter and 31 m length (Fig. 9). As it can be seen from Tab. 2, excellent consistency between measurement results exists under the full load conditions. However, the discrepancy rises systematically with falling discharge. At the lower edge of the guaranteed range (14 m^3/s) the pressure-time method data fall by 2% below those attained by means of the current-meter methods when the ISO 3354 and the IMP PAN cubic spline integration schemes are used, respectively. The discrepancy between velocity field integration results does not exceed 0.2% except for the last measurement, which has shown relatively high irregularities in velocity profiles. Generally, the cubic spline approach results in slightly smaller discharge than the ISO 3354 one. This typical effect was noticed by the authors on numerous occasions in the early stage of the cubic spline scheme development.

Table 2: Discharge measurement results attained at unit 2 in Zur HPP by means of the ISO 3354 (CM1) and the IMP PAN cubic spline (CM2) current-meter techniques as compared with those following from the pressure-time (PT) method [23].

Test run	47	48	49	50	51	52	53	54	55	56	57	59	60
CM1, m^3/s	35.56	33.57	30.57	27.19	24.46	21.77	19.34	17.35	15.18	13.22	11.27	7.79	6.35
CM2, m^3/s	35.50	33.52	30.52	27.14	24.42	21.74	19.31	17.33	15.15	13.24	11.25	7.78	6.39
PT, m^3/s	35.55	33.66	30.31	27.05	24.13	21.45	19.04	17.06	14.86	12.83	11.00	7.56	6.27
δ_{CM1}, %	-0.16	-0,15	-0.17	-0.17	-0.15	-0.15	-0.17	-0.13	-0.17	0.17	-0.20	-0.15	0.61
$\delta_{PT/CM1}$, %	-0.02	0.27	-0.86	-0.50	-1.34	-1.48	-1.57	-1.69	-2.08	-2.94	-2.41	-2.98	-1.28

As shown in reference [18], the maximum discrepancy between the current-meter and pressure-time methods does not exceed the 1% threshold in case of using the NURBS scheme for velocity field integration. This shows that some further studies on the nature of discrepancies observed may be recommended. The qualitative analysis of derived velocity profiles – especially in peripheral zones – seems particularly worthwhile if the physical background is to be properly understood.

The rise of discrepancy between the pressure-time and the current-meter method at low discharge range is not astonishing as the accuracy of Gibson method is known to decrease gradually as the LV product of the measurement segment length L and the mean velocity V falls. The $LV = 50$ m^2/s value at full load operation is considered the lower limit of the method validity according to IEC

Figure 9: Current-meters and the Gibson method impulse tubes in the penstock of Zur hydropower plant.

60041. On the other hand, the limited validity range of current-meter calibration characteristics should not be ignored either.

2.4 Acoustic methods

High accuracy multipath transit type acoustic flowmeters are used mainly in large tunnels and penstocks, especially for water flow counting purposes [24]. Portable Doppler and transit time meters have been used by IMP PAN on several occasions for testing small units with relatively long penstocks [25]. These single path devices, incompatible with most commercial acceptance test codes, provide reasonable results under favourable conditions. Due to simple installation and easy handling they can be really recommended whenever high accuracy is not required.

Acoustic scintillation of a hydrometric section in water intakes [26] seems a promising alternative to using component current-meters in highly nonuniform velocity fields. Unfortunately, the velocity field nonuniformity is often due to turbulent flow disturbances, which distort effectively the acoustic signal and lower the measurement accuracy. This technique has never been used by the IMP PAN team.

3 Cam curve optimisation

As already mentioned, cam curve optimisation is an essential part of commissioning and/or acceptance tests of new double regulated turbines. However, even in

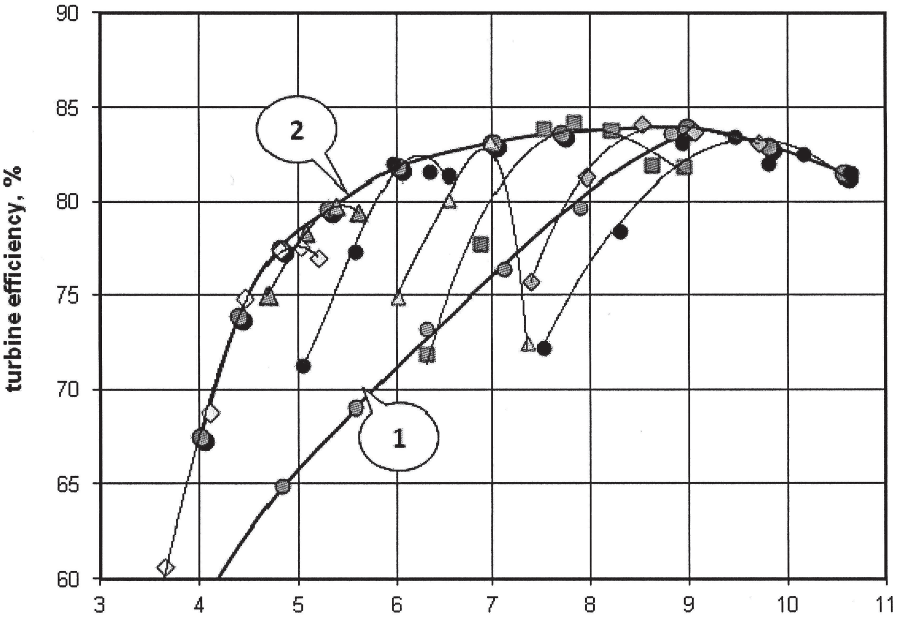

Figure 10: Efficiency increase as a result of cam curve optimisation in an old Polish hydropower plant with vertical Kaplan turbine (P = 380 kW, H = 4.5 m): 1 – original efficiency curve resulting from distortion of kinematic dependencies in the turbine control mechanism, 2 – propeller efficiency curves with an envelope showing efficiency to be attained after cam curve optimisation.

case of older machines this may appear required as numerous overhauls and rehabilitation of control system components often result in deregulation of kinematic dependencies between positioning of the mechanical control system components. A typical result is to be seen in Fig. 10 showing an old unit efficiency curve prior and after cam curve optimisation.

The technique applied for cam curve optimisation has been described in detail in numerous classic textbooks and monographs. The envelope of a series of efficiency propeller characteristics is used together with the series of relevant wicket gate opening vs discharge curves. In case the accurate absolute discharge measurement is too expensive and/or technically problematic, index tests may be used as well. Differential pressure methods, as recommended by the IEC 60041 code, are the most popular ones. Cam curve optimisation using pressure taps located at the flow field stagnation point and at the turbine casing upstream the wicket gate cascade is a routine procedure applied during the double-regulated tubular turbine commissioning tests. Winter-Kennedy technique, based on measurement of differential pressure between the outer and inner sides of the spiral casing [27], is traditionally used for classic Kaplan turbines. In case the pressure measurement installation has not been originally supplied or has been found in poor condition, the pressure tap strips with copper impulse tubing are mounted from inside on the streamlined casing surface. The other option is using simplified current-meter technique as mentioned in Section 2.2.

Some small double-regulated units (e.g., those with Kaplan turbines installed in an open chamber or submersible ones) are delivered without the differential pressure measurement taps. If no abso-lute or index (e.g. current-meter) discharge measurement is planned, the suppliers often use either the design setting or the dependence established by means of testing power/wicket gate opening correlation for different runner blade openings. Few years ago accuracy of the last procedure was tested by the IMP PAN team using the efficiency index

$$\eta_{ind} = \frac{P/Y_0}{(P/Y_0)_{max}} \times 100\% \tag{22}$$

with P standing for power output as reduced to some reference head and Y_0 – wicket gate servomotor piston stroke. The use of this index is based on a very rough assumption that in case of constant runner blade setting, the discharge may be considered a linear function of the wicket gate opening or servomotor piston stroke. In Fig. 11 three cam dependences as established for a small Kaplan turbine in Owidz SHP ($P = 245$ kW, $H = 3.50$ m) are shown: the original dependence as set by the supplier for the design head of 3.5 m, cam dependence established for 3.0 m head basing on the current-meter tests [28, 29] and the dependence determined for the same head using solely the efficiency index procedure. As it can be seen from the figure, the simplified procedure, based on maximisation of the efficiency index value, has resulted in a proper trend in the cam dependence shift. However, substantial scatter of the data points and a 5% discrepancy with the curve determined by means of an absolute discharge measurement prove clearly the limited reliability of this approach.

4 Performance curves and optimisation of the hydropower plant operation

The final goal of numerous performance tests is optimisation of the hydropower plant operation meant in terms of maximising the owner's income. As all Polish SHPs are paid only for supplied electricity now, this implies maximisation of electricity generation while keeping to the requirements of the water legal licence. For

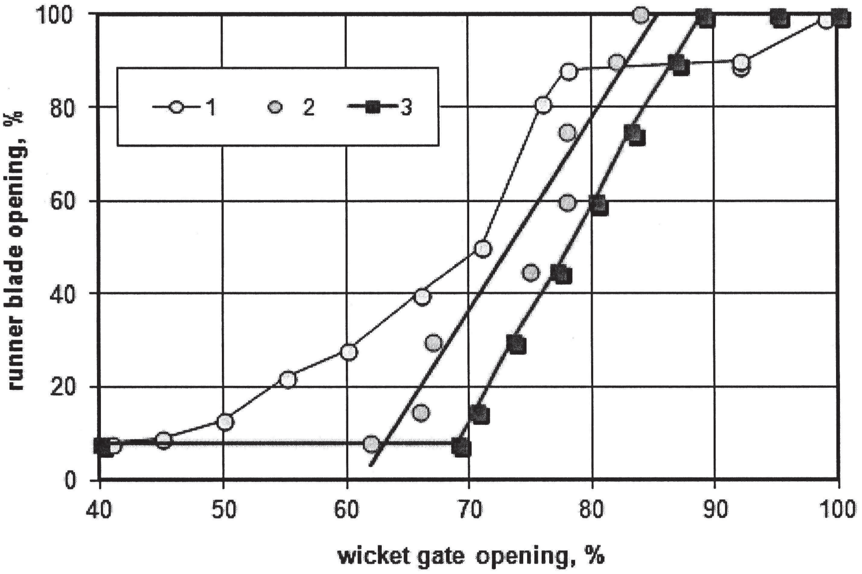

Figure 11: Cam curves of a small Kaplan unit following from various procedures: 1 – design curve established by the turbine supplier for $H = 3.5$ m rated head and coded originally into the governor; 2 – approximate curve established in result of the efficiency index maximisation at $H = 3.0$ m head; 3 – cam curve resulting from a comprehensive performance test performed at $H = 3.0$ m head.

this purpose it is essential to use available performance characteristics in order to distribute properly the load between the units.

The performance characteristics delivered in result of a low head SHP unit test include as a rule unit output and efficiency vs discharge or wicket gate opening curves at a given gross head. These curves are used later on to derive the power plant specific water consumption characteristics corresponding to the optimised load distribution between the units. The curves corresponding to the same head in Niedalino SHP (Fig. 12) [30] do not intercept each other. This shows there exist flow regimes in which some part of in flowing water should be rather discharged through a spillway or some other relief device than through the next turbine. Steep efficiency characteristics of Francis turbines in Niedalino are responsible for this situation.

Supplementary performance curves, including discharge vs. wicket gate opening, are usually incorporated into the final test report as well. The hydraulic unit or turbine quality is assessed by referring all performance characteristics to the net head or specific energy as required by the IEC 60041 code.

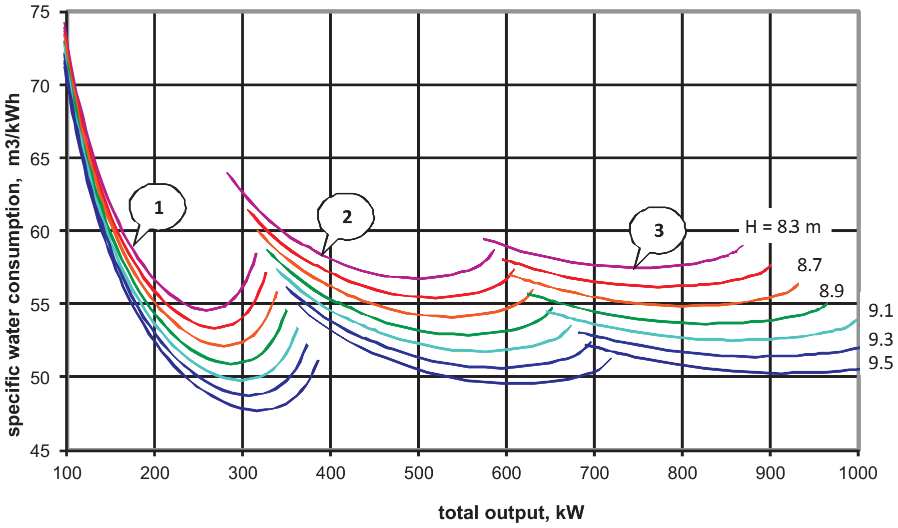

Figure 12: Specific water consumption curves of the Niedalino SHP under optimised strategy of running hydraulic units at heads ranging between 8.3 and 9.5 m: 1 – unit 2; 2 – unit 2 and 3; 3 – all units in operation.

In case of old installations determining turbine performance characteristics may appear problematic due to scarce access to the generator efficiency data. Use is made sometimes of statistically determined efficiency dependencies on the rated apparent power, active power coefficient and the actual electrical output, e.g. [31]. However, the characteristics derived in result of such a procedure may serve barely for rough assessment purposes.

5 Conclusion

1. Despite immense progress in discharge measurement techniques, this part of the hydraulic unit performance tests is often a major challenge even for experienced test teams.
2. The above refers in particular to low head installations where the measurement at water intake is often the only option. The use of component current-meters seems still the most reliable approach in such a case although further progress in velocity field scintillation techniques may change this situation.
3. Numerous velocity field integration techniques have been widely used by

various teams for tens of years, showing often practical superiority over those recommended by the ISO 3354 standard. The IMP PAN experience shows that high coincidence is usually achieved under flow conditions corresponding to those required by the IEC 60041 code. One of such algorithms has been outlined in this paper.

4. Simplified methods, based on vibration tests and wicket gate opening / power output relation-ships are used sometimes to establish the optimum cam dependence of double-regulated turbines without discharge measurement. Due to limited accuracy, these approaches may be recommended only for establishing temporal (preliminary) settings in small units.

Acknowledgment This paper summarises a significant portion of expertise collected by the authors during performance tests conducted at small hydropower installations owned by various Polish companies, including *Energa Hydro* (currently *Energa Wytwarzanie*) Sp. z o.o., *Enea Elektrownie Wodne* (currently: *Enea Wytwarzanie*) Sp. z o.o., *ZEW Niedzica* S.A., *ESP* S.A. (currently: *PGE EO* S.A.) and *Jeleniogórskie Elektrownie Wodne* (currently: *Tauron Ekoenergia*) Sp. z o.o. Photographs and some test results of *Energa Wytwarzanie* SHPs are used on numerous occasions to illustrate considerations presented in this paper. Photos of discharge measurement equipment and results obtained during acceptance tests at Żur Hydropower Plant (owned by *Enea Wytwarzanie*) are used for the purpose of comparative analysis presented in Subsection 2.3. Use has been also made of a design drawing prepared under contract with *ZEW Niedzica* for the purpose of discharge measurements in Laczany SHP. All named companies are highly appreciated for their good collaboration and technical support. Particular thanks are due to *Energa* and *Enea Wytwarzanie* companies for their consent to illustrate the paper with selected test results.

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