SVENSKT VATTENKRAFTCENTRUM

Flow Measurements in Low-Head Hydro Power Plants

Elforsk report 12:61

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ELFORSK

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Foreword

The purpose of the work presented in this report was to address the challenge of flow measurements in low head hydraulic turbines. Accurate efficiency measurements are of importance when evaluating the efficiency after a refurbishment. Increases in efficiency are stimulated by the Government through the electricity certificate system.

The report was written by Michel Cervantes and Joel Sundström, Luleå University of Technology, Gunilla Andrée, Vattenfall Research and Development and Peter Klason, SP Technical Research Institute of Sweden.

A working group, with representatives from the hydro turbine industry in Sweden (Urban Andersson, Alstom, Niklas Dahlbäck, Vattenfall, Rolf Johansson, Norconsult, Maria Lindegren, Norconsult, Henrik Lindsjö, Andritz, Daniel Litström, Pöyry, Magnus Lövgren, Vattenfall, Stefan Sandgren, EON, Mikael Sendelius, Sweco and Anders Skagerstrand, Vattenfall), has also contributed to the project. The workgroup has met several times to share and discuss experiences, visions and goals. All efforts are highly appreciated.

The work presented in this report was carried out as a part of "Swedish Hydropower Centre - SVC". SVC was established by the Swedish Energy Agency, Elforsk and Svenska Kraftnät together with Luleå University of Technology, The Royal Institute of Technology, Chalmers University of Technology and Uppsala University. Participating hydropower companies are: Alstom, Andritz Hydro, E.ON Vattenkraft Sverige, Fortum Generation, Holmen Energi, Jämtkraft, Karlstads Energi, Linde Energi, Mälarenergi, Skellefteå Kraft, Sollefteåforsens, Statkraft Sverige, Statoil Lubricants, Sweco Infrastructure, Sweco Energuide, SveMin, Umeå Energi, Vattenfall Research and Development, Vattenfall Vattenkraft, VG Power and WSP.

More information about SVC can be found on www.svc.nu.

Stockholm, November 2012

Cristian Andersson
Program area Hydropower
Elforsk

Sammanfattning

Vattenkraft står för ca 50% av elproduktionen i Sverige. De flesta av verken byggdes för flera årtionden sedan och kommer successivt att behöva förnyas. Förnyelsen har påbörjats och kommer kontinuerligt att fortsätta. Betydande produktionsvinster och anpassning till nya marknadskrav kan uppnås i förnyelsen och den stimuleras också av staten genom elcertifikatsystemet. Verkningsgradhöjningar är således av vikt, men utgör en utmaning i de lågfallhöjdsmaskiner (H <50 m) som dominerar i Sverige. Under de senaste decennierna har Winter-Kennedy metoden använts för att kontrollera förbättringar av verkningsgrad genom att mäta före och efter en renovering. Resultaten har i ett antal fall visat oförutsägbara resultat. Det finns ett behov av utveckling för att noggrant mäta verkningsgrad för att utvärdera resultatet av olika förnyelseprojekt.

En arbetsgrupp har därför bildats inom Svenskt VattenkraftCentrum med representanter från vattenkraft- och turbinbranschen i Sverige för att identifiera insatser för att utveckla flödesmätning i lågfallhöjdsturbiner. I denna rapport presenteras olika flödesmätningsmetoder som finns med deras utvecklingsstatus och potential att möta behoven för lågfallhöjdsmaskiner.

Arbetsgruppen föreslår flera insatser för att utveckla flödesmätning i lågfallhöjdsmaskiner. De är indelade i två kategorier: lång och kort sikt. De långsiktiga insatserna är typiska SVC-projekt för doktorander och/eller seniora forskare, medan de kortsiktiga insatserna är projekt för konsult och/eller seniora forskare. Följande insatser föreslås i prioritetsordning:

Långsiktiga projekt

1. Utveckling av ”pressure-time”-metoden som en absolut och relativ metod
2. Utvärdering av skallagar och inflytande av parametrarna som skiljer sig mellan modell och prototyp, såsom spiralens inloppsrandvillkor

Kortsiktiga projekt

1. Vägledning för genomförande, utvärdering och rapportering av flödesmätningar med Winter-Kennedy metoden. Fortsätta arbetet med de gemensamma riktlinjer som utarbetats i SEK-TK4.
2. Systematisk felanalys av flödesmätningar med Winter-Kennedy metoden
3. Test av den volymetriska metoden på en fullskalig turbin för att undersöka möjligheter och utvärdera nödvändig utvecklingsbehov för lågfallhöjdsmaskiner
4. Test av ”dilution” metoden på en fullskalig turbin för att undersöka möjligheter och utvärdera nödvändig utvecklingsbehov för lågfallhöjdsmaskiner

Summary

Hydropower stands for a large part of the energy production portfolio in Sweden and provides about 50% of the electricity needs. Most of the turbines were built some decades ago and are in a need of refurbishment. An important refurbishment period started some years ago and will be continuous. Substantial production gains and adaptation to new market demands may be achieved with such refurbishments. Refurbishments are also stimulated by the government through the electricity certificate system. Efficiency step-ups are thus of importance but challenging due to the presence of mainly low head (H<50 m) machines in Sweden. During the last decades, the Winter-Kennedy method has been used to verify improvements of the efficiency by measuring before and after a refurbishment. The results have for a number of cases shown unpredictable results. There is a need of development to measure accurately the efficiency in order to evaluate the outcome of different refurbishment projects.

A workgroup within the Swedish Hydropower Centre (Svenskt Vattenkraftcentrum, SVC) has been formed together with representatives from the majority of the hydro turbine industry in Sweden to address the challenge of flow measurements in low head hydraulic turbines. The present report presents the different methods available with their actual development status and potential to meet low head hydraulic machines constraints.

The working group suggests several actions for the development of flow measurements in low head machines. They are divided in 2 categories: long term and short term. The long term actions are typical SVC projects for PhD or/and senior researcher while short term actions are projects for consultant or/and senior researcher. The following actions are suggested in a hierarchical order:

Long term projects

1. Development of the pressure-time method as an absolute and relative method
2. Evaluation of scale-up formula and influence of the parameters differing between model and prototype such spiral inlet boundary conditions

Short term projects

1. Procedure/road book for implementation, evaluation and reporting of the Winter-Kennedy method. Continue working on the common guideline drafted in SEK-TK4.
2. Systematic error analysis of the Winter-Kennedy method
3. Testing of the volumetric method on a full-scale unit to investigate capabilities and evaluate necessary development for low head hydro power plants
4. Testing of the tracer dilution method on a full-scale unit to investigate capabilities and evaluate necessary development for low head hydro power plants

Contents

1 Introduction

1.1 Problem description

Hydropower stands for a large part of the energy production portfolio in Sweden and provides about 50% of the electricity needs. Construction of new hydropower plants is not actual in Sweden since the remaining unexploited rivers are protected according to law. However, most of the turbines were built some decades ago and are in a need of refurbishment. An important refurbishment period started some years ago and will be continuous. Substantial production gains and adaptation to new market demands may be achieved with such refurbishments. A few tens of a percent increase in the turbine efficiency can lead to a significant increase in cost efficiency. Furthermore, investments in environmental friendly production are stimulated by the government through the electricity certificate system, which has been in operation since 2003. In refurbishment projects, the efficiency increase gained is regarded as renewable energy by the authorities. The green certificate meant an increase in value, for the hydraulic power owners, of about 60% for each kW produced compared to the market value during the last five years. The green certificate is thus important when taking the decision about reinvestments. Nevertheless, accurate efficiency measurements are of importance to verify these improvements for turbine owners, authorities and manufactures [1].

Accurate efficiency measurements in prototype, both absolute and relative, are challenging in low head machines (<50 m) due to the short water passages and geometrical variations. Most of the methods necessitate measurement of the flow rate, which is the main challenge. Several absolute methods have been developed and accepted as standard [2]: current meter, Pitot tubes, pressure-time (Gibson's) and tracer methods. The thermodynamic method allows measuring directly the efficiency for head exceeding 100 m, successful measurements for 50 m head have been reported by the Norwegian University of Science and Technology (NTNU), Norway [3]. Similarly, the pressure-time method necessitates some conditions for good results such as a straight inlet of at least 10 m. Development are going on at Luleå University of Technology (LTU) for application to low head machines [4]. The work handles straight penstock outside the IEC41 standard by using a modified procedure. The initial results are promising and should be extended to more complex geometry. Ultrasound methods are becoming more popular. Three different techniques are available: transit-time, cross-correlation and Doppler. The transit time method is expected to be a reference method in the updated IEC41 standard. Cross-correlation and Doppler method have been developed during the last years with variable results [5].

Relative methods, generally used during the commissioning and operation of the machines, are extremely popular in Sweden. The popularity is mainly due to the low head of the Swedish turbines, which makes an absolute measurement difficult due to a large absolute uncertainty, and because they can be executed at an attractive cost: a decade below other types of absolute measurements. The most popular method used is the Winter-Kennedy method. The ultrasonic method is also used in some cases but has a prohibitive cost compared to the Winter-Kennedy. The Winter-Kennedy method allows determination of the relative performance changes in the turbine by measuring the pressure difference between 2 or 4 pressure taps in the spiral casing at 1 or 2 sections [2]. The method is therefore sensitive to modifications/conditions altering the pressure in the spiral. A refurbishment may involve many modifications in the turbine near the spiral, e.g. new stay vanes profile, new guide vanes, new runner, re-painted spiral, renovated pressure taps, etc. Hence, the flow pattern in the spiral case may differ from the original. Similar pressure measurements after refurbishment are not either a guarantee for a successful determination of the relative efficiency step-up because the same error introduced at both pressure taps may cancel each other out. Since many years, the validity and area of application of the Winter-Kennedy method have been discussed.

In summary, efficiency measurements and more specifically flow rate measurements in low head hydraulic turbines (<50 m) is a common problem to the entire hydropower industry in Sweden. There is a need to develop accurate methods for such measurements. The present document aims to present a summary of the methods available for such measurements with their strength(s), drawback(s) and development potentials. Further development of specific methods to ensure accurate efficiency measurements in low head machines is presented after an analysis of the methods.

2 Objectives

The main objective of the present work is to produce a document supporting the Swedish hydropower industry for planning their future research and development activities within flow measurements in low head hydraulic turbines. To this purpose, the documents comprise:

- The different flow measurements methods available for low head hydraulic machines including theoretical description, implementation, experience, error analysis as well as description of the development potential method when possible.
- An analysis and discussion of the different methods available.
- Suggestions for further research and development projects presented in a hierarchical manner.

3 Methodology

A workgroup within the Swedish Hydropower Centre (Svenskt Vattenkraftcentrum in Swedish, SVC) has been formed together with representatives from the majority of the hydro turbine industry in Sweden to address the challenge of flow measurements in low head hydraulic turbines. The workgroup has met several times to share and discuss experiences, visions and goals. The report was produced by reviewing information and material from the workgroup together with technical research papers and reports on the topic. Contacts were established with other research and technical institutes actively working within the field of flow measurements.

The people involved in the working group beside the authors of the documents were:

- Urban Andersson, Alstom
- Niklas Dahlbäck, Vattenfall
- Rolf Johansson, Norconsult
- Maria Lindegren, Norconsult
- Henrik Lindsjö, Andritz
- Daniel Litström, Pöyry
- Magnus Lövgren, Vattenfall
- Stefan Sandgren, EON
- Mikael Sendelius, Sweco
- Anders Skagerstrand, Vattenfall

4 Relative Measuring Methods

4.1 Winter-Kennedy Method

The Winter-Kennedy method is an index method, IEC41 [1], often used for relative measurement of the efficiency of a hydraulic turbine in Sweden. It was I. A. Winter and A. M. Kennedy [2] who found that the pressure difference, ΔP, between 2 points at the same radial line in the spiral casing of a turbine, see Figure 4.1, could give an indication of the discharge through the relation: $Q = K \cdot (\Delta P)^n$, where K is known as the flow coefficient. The discharge of the turbine can be described as a function of the square root of the differential pressure obtained from the Winter-Kennedy pressure taps; Schweiger [3], Brice et al. [4] and Sheldon [5].

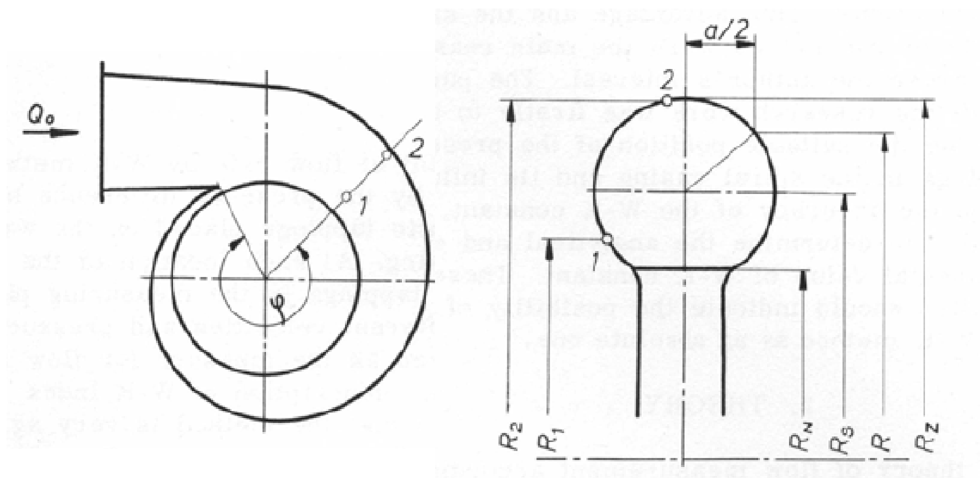


Figure 4.1 - Sketch of spiral with denotation for the Winter-Kennedy method, IEC41 [1].

4.1.1 Theory

A flow in a curved pipe is subject to a centrifugal force function of the radius. Assuming a laminar, steady and non-viscous flow as well as negligible radial (toward the runner) and vertical velocity components, the radial component of the Navier-Stokes equation is given by:

$$\frac{u_\theta^2}{r} = \frac{1}{\rho}\frac{\partial P}{\partial r}$$

Where u_θ, r, P and ρ are the tangential velocity (normal velocity at each section of the spiral casing), the radial position relative to the spiral casing center, the pressure and the density, respectively. Integration with respect to *r* and *P* assuming $Q=u_\theta.A$ (u_θ is assumed constant across the considered section), gives the flow rate function of the pressure across 2 points in the spiral:

$$Q = A\sqrt{\frac{P_2 - P_1}{\rho \cdot \ln\left(\frac{R_2}{R_1}\right)}}$$

The flow through the section may thus be written:

$$Q = K \cdot \sqrt{\Delta P}$$

Where

$$K = \frac{A}{\sqrt{\rho \cdot \ln\left(\frac{R_2}{R_1}\right)}}$$

In the IEC41 standard [1], it is given as:

$$Q = K \cdot (\Delta P)^n$$

where *n* may vary between 0.48-0.52 and *K* needs to be determined. The variation in *n* is not physical as mentioned by Nicolle and Proulx [7].

4.1.2 Measuring Procedure

To measure the volume flow using the Winter-Kennedy method, at least 2 pressure taps should be located on the spiral casing: one in the inner part and one in the outer part, see Figure 4.1. The inner tap should be placed just outside the stay vane. The taps need to be positioned in the same radial section of the spiral casing. Another pair of pressure taps located in another radial section is recommended. This applies to both steel spiral and semi-spiral concrete casings. The differential pressure is then measured between the inner and the outer wall and related to the flow as described above. To achieve an accurate measurement it is important to perform model test homologue to the prototype to get the efficiency curve. An accurate differential pressure sensor within the required range is required.

Beside the pressure, the head should be measured to obtain the efficiency. This is usually done with one drainable pressure sensor in the head water and one in the tail water. The power should also be recorded.

The flow coefficient, *K*, for the prototype is usually determined using the results of a model test. The prototype efficiency at the best efficiency point (BEP) is obtained by scaling-up the model efficiency at BEP, IEC60297 [8]. The expected prototype flow rate is thus determined from the prototype power output and head at BEP. The coefficient *K* thereafter obtained using the theoretical flow rate and the differential pressure measured at BEP. Any other point could be used, e.g., the maximum power output.

4.1.3 Problems Encountered

The method has been used in some projects to verify performance improvements of turbine after upgrading during the last 8-10 years, mainly in connection to green certificate applications. Some problems have been encountered. A main issue is the inconsistency in the results obtained, e.g., with the common assumption that the flow coefficient is not affected by the upgrading of the unit, the new runner may sometimes get a lower efficiency than the old one. Several reasons may cause the discrepancies:

- old pressure taps, which have not been inspected or renovated for years (surface irregularities may be present)
- variation in the roughness of the guide vanes and runner between the first and second measurements may affect the results.
- modification of the geometry in the spiral casing affecting the differential pressure to be measured (new runner, new guide vanes, new stay vanes, painted spiral casing,...)
- different operational conditions of the neighboured turbines at each test
- the boundary layer might differ before and after refurbishment influencing the pressure drop. The Winter-Kennedy measurement made before the refurbishment projects is made on a surface that is rough due to corrosion, after refurbishment the surface is often smooth as the spiral casing is painted. The surface roughness might influence on the pressure measurements.

Inspection of the pressure taps is surprisingly rarely performed prior to a measurement. This is mainly due to limited access to the pressure taps and time constraints in the projects. However, this may be easily avoided if the measurements are planned beforehand.

4.1.4 Error Analysis

Andersson et al. [6] investigated the effect of skew inlet flow on the Winter-Kennedy method in a turbine model test. A deviation of up to 10% related to the skew inlet flow was found. Nicolle and Proulx [7] investigated the method numerically and experimentally. They estimated the effects of the inlet boundary conditions to influence the results as much as 5.4%. Also very interesting was the linear relation between K and the guide vanes angle, i.e., K was not constant.

Overall, there is not any systematic error analysis of the Winter-Kennedy method as well as a quantification of its limitations. Thus work is necessary.

4.1.5 Cost and downtime for hydropower unit

If pressure taps are already installed and no additional inspection or refurbishment is made of the pressure taps, the indicative cost for measurement using the Winter-Kennedy method is in the order of 200 KSEK.

An inspection of the pressure taps and a possible refurbishment increase significantly the cost as the waterways must be dewatered. However, such action may be included at an early stage during maintenance when water ways are dewatered.

4.1.6 Further Development

The Winter-Kennedy method is certainly the most cost effective method as most of the turbines have pressure taps for such measurements. However, the discrepancies in the results, difficult to clearly explain, make such method difficult to choose even for a relative measurement.

A systematic error analysis and limitations of the Winter-Kennedy according to the layout presented in the IEC41 standard [1] should be done. A common procedure to perform and evaluate Winter-Kennedy measurements is also required. The main objectives of such work will be to give a common foundation to utilities, authorities, suppliers and consultants performing such measurements for discussion concerning implementation, evaluation and expectation of measurements with the present method.

Resent developments of the method have been performed by Nicolle and Proulx [7, 8] at Hydro-Quebec. After a numerical investigation of the method, they proposed a new position of the inner pressure tap to increase the differential pressure and thus make the measurements more robust. The new configuration is however sensible to the guide vanes position and thus requires a calibration curve relating the constant K to the guide vanes angle. Dewatering of the tubes coupling the taps to the differential pressure sensors was avoided by the use of automatic bleed valves. The new configuration has been tested successfully for continuous online measurements. Work to continue developing this method would be of interest to decrease the uncertainty.

4.1.7 References

[1] IEC41, 1991, *International Standard – Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines*, volume 41, Geneva, Switzerland, third edition.

[2] Winter I. A., *Improved type of flow meter for hydraulic turbines*. Proceedings of the American Society of Civil Engineers, Volume 59, No. 4, part I, April 1933.

[3] Schweiger F., *Research work on flow measurement by the Winter-Kennedy method*. Flow Measurements of Fluids by Dijstelbergen, H. H., E. A. Spencer, 1978.

[4] Brice T. A. and Kirkland J. E., *Checking turbine performance by Index Testing*. Proceeding of Waterpower, pp 1002-1011, 1985.

[5] Sheldon L. H. *Field testing and optimising efficiency of hydro turbines*. Water Power & Dam Construction, 1982.

[6] Andersson U., Lövgren M. and Andrée G., *Skew inlet flow in a model turbine, effects on Winter-Kennedy measurements*. Hydro 2008, Ljubljana, Slovenia, 2008.

[7] Nicolle J. and Proulx G., 2010. *A new method for continuous measurements for hydraulic turbines*. IGHEM 2010, IIT Roorkee, India.

[8] Nicolle J. and Proulx G., 2012. Online flowrate monitoring experiences at Hydro-Québec. IGHEM 2012, Trondheim, Norway.

[8] IEC62097, 2009, *International Standard – Hydarulic machines, radial and axial – Performance conversion method from model to prototype*, Geneva, Switzerland, Edition 1.0.

4.2 Hybrid Method

Hybrid methods are developed as alternative to existing relative methods such as the Winter-Kennedy. The related cost should be similar to the existing relative methods and thus simple to implement. They may e.g. be composed:

- 1 current meter + Winter-Kennedy
- 1 ultrasonic pass + Winter Kennedy

All absolute methods may also be used as a relative method. Andersson et al. [1] tested a simplified transit time measurements using a 1 path (instead of 8) configuration as a relative method. The layout was not accurate enough to detect variation in the profile introducing large error.

The use of an absolute method as a relative method or a combination of two methods may look very attractive. However, such measurements are not straightforward as many questions arise due to a lack of knowledge since not previously systematically investigated. Furthermore, the absolute methods are usually used in a simpler configuration to reduce cost. To the authors knowledge, there is not today any reliable relative method (of any kind) working perfectly in low machine (H<50 m).

4.2.1 Theory

The theory of some individual method is treated in different sections, see content.

4.2.2 Measuring Procedure

The measurement procedure for hybrid methods may be a combination of individual method procedure with some variation and is not treated.

4.2.3 Problems Encountered

The problems encountered are specific to the methods chosen and are not treated.

4.2.4 Error Analysis

The use of an absolute method as a relative method is very attractive as the systematic error is removed from the error analysis. The uncertainty or random error is the only part left in the error analysis. The reader is therefore invited to read the error analysis of individual methods, see content.

4.2.5 Cost and downtime for hydropower unit

The cost and downtime of such method should of course be significantly lower than an absolute measurement and of the same order of magnitude as a known relative measurement. The cost and downtime of several methods are treated in the present document, see content.

4.2.6 Further Development

A relative method should be cost effective, i.e., production should not be perturbed and the implementation pretty fast. Therefore, a relative method should only involve the plug in of some sensors.

The pressure-time method is very attractive to this purpose. Most hydraulic machines have pressure taps at the inlet of the spiral casing. The relative flow may thus be determined between the spiral casing inlet and the free surface. As the measurements are relative, correct determination of the viscous curve losses during closure is not necessary as long as they are treated similarly between both measurements. The pipe factor is not either required. The development as a relative method is discussed in the following section where the pressure-time method is treated.

4.2.7 References

[1] Andersson U., Dahlbäck N. and Sundqvist P. *Accuracy of an absolute method used for relative measurements: study of an acoustic transit time method.* IGHEM 2010, IIT Roorkee, India.

5 Absolute Measuring Methods

5.1 Pressure-time Method

The pressure-time method was developed nearly a century ago, Gibson [1]. It is accepted as an absolute method to determine the flow rate and included in the IEC41 standard [2]. It may be used under certain conditions, to be presented below, with an overall uncertainty at the 95% confidence level below ±1% [5].

The IEC41 standard, *Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines*, dates from 1991; the differential mercury pressure gauge is e.g. presented. It has been much development in sensor and computer technology since 1991. However, development of the method has been restricted. Since some years, work on the method has been performed at Luleå University of Technology, Jonsson [3], for application to low head machines with encouraging results.

The following text is structured as the previous chapters; theory, measuring procedure, problem encountered, error analysis and further development.

5.1.1 Theory

The pressure-time method is based on the change of momentum of the fluid into pressure during closure of the guide vanes. By measuring the pressure variation between two different sections, the force acting on the fluid volume between the two sections may be related to the fluid acceleration, and thus the flow rate after integration. The pressure variation may be measured differentially or at each section. One of the sections may be the inlet free surface, a suitable alternative for low head machines.

Change of momentum may be obtained by gradually closing the guide vanes from a prescribed steady state. The flow rate Q through the turbine before gradually closing the guide vanes is obtained from the differential pressure between both sections using the following formula:

$$Q = \frac{A}{\rho L}\int_0^t (\Delta P + \xi)dt + q_0$$

where q_0 is the leakage flow when the guide vanes are closed, t the time, ξ the friction losses, ΔP the pressure difference between both sections, A the cross section area, ρ the fluid density and L the distance between both sections.

A typical closure process obtained from a numerical simulation is presented in Fig. 5.1.1. From t=0 to about 1 s, the flow is steady. During this period of time, the mean velocity between both sections (pressure-time's integrated velocity, black line) is constant and the differential pressure between both sections (green line) represents the viscous losses (red line), i.e., pressure losses for a pipe flow.

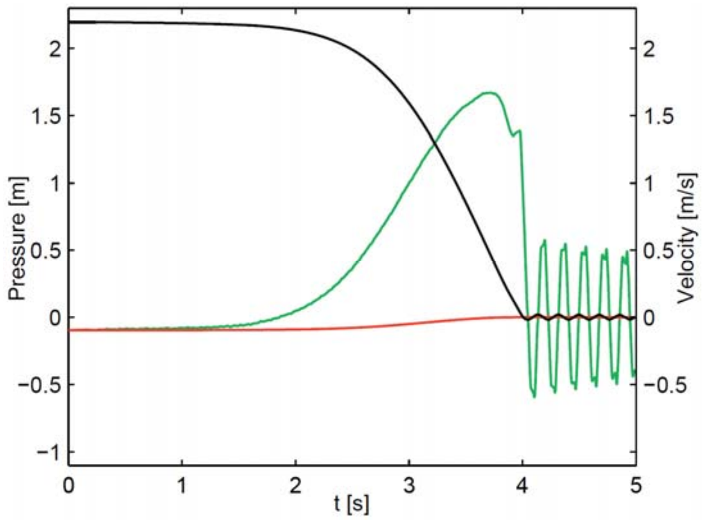


Fig 5.1.1 – Variation of the differential pressure (green line) between 2 sections during a pressure time measurement. The black line represents the mean velocity and the red line the viscous losses between both sections. Data obtained from a simulated valve closure using a 1 dimensional model ($Re=10^6$, D=0.3 m), Jonsson [2].

At t=1 s, the valve starts to close. The mean velocity decreases up to t=4 s, indicating a stationary flow between both sections. Thereafter, oscillations appear due to the pressure waves travelling between the valve and upstream boundary. The amplitude decreases with time due to the viscous losses.

Determination of the viscous losses between both sections is made assuming a quasi-steady flow and rough surface. The assumption of a quasi-steady flow means that the flow can be assumed steady at every time, i.e., the effects of unsteadiness are neglected. Rough surfaces have the peculiarity to have a constant friction factor over a wide range of Reynolds number; this assumption facilitated the flow calculation, when integration of the pressure was made without the help of a computer. This assumptions will be further discussed below, in the section Further Development (5.1.5).

The friction factor is determined from the pressure measurements under steady conditions before closure. The integration of the pressure is obtained through an iterative process. An initial linear viscous loss is assumed from which a velocity is obtained. The new velocity is used to repeat the procedure until convergence is obtained.

5.1.2 Measuring Procedure

Several conditions are required to perform measurements with the pressure-time method according to IEC41 [2]. The most significant constraints are listed below:

- Within the measuring reach the conduit shall be straight and have a constant cross-section and not present any significant irregularity.
- The distance between the two measuring sections shall not be less than 10 m. The cross-sectional areas of the conduit and the length of the measuring reach between the two cross-sections shall be measured in the field with sufficient precision to determine the pipe factor F (ratio of the length to the diameter) within an accuracy of 0.2%.
- The product of the length between the two pressure measurement sections and the mean velocity in the pipe when the unit is carrying full load shall not be less than 50 m^2/s.
- The leakage through the closed gate in the test conditions shall not be greater than 5% of the discharge being measured and shall be measured within an accuracy of 0.2% of that discharge.
- The sum of the pressure loss between the two measuring sections and of the dynamic pressure, at the maximum discharge to be measured, shall not exceed 20% of the average change in differential pressure as recorded while closing the gate.
- No intermediate free surface shall exist between the two pressure measurement sections.

The parameters to be measured simultaneously during the gradual closure of the guide vanes are the pressure between the two sections, guide vanes position and water temperature.

Four pressure taps separated by an equal angle are recommended at each section. None should be positioned on the top or the bottom of the section. Furthermore, a minimum distance of 2 diameters is recommended between the sections and no significant irregularity in the conduit. The dimensions of the pressure taps should be chosen according to a standard, e.g. ASME, and of course inspected. Inadequate pressure taps may be the source of large errors.

The use of differential or absolute pressure sensors in well controlled laboratory conditions did not point out any major differences, see Jonsson [3]. However, differential pressure sensors are preferred when their use is possible together with connecting tubing of the same length. One drawback of absolute pressure sensors is the difficulty to determine the end point for integration due to the presence of large fluctuations. The second disadvantage of absolute sensors is their larger relative error as they need to measure larger pressure than the one of interest. In summary, differential pressure sensors are recommended.

5.1.3 Problems Encountered

The main problem encountered in the use of the pressure-time method is in this context the difficulty to apply it to low head machines due to the constraints stipulated in the IEC41 standard. The necessity of a straight conduit of at least 10 m, UL>50 m^2/s and a distance of at least 2 diameters between the section and any significant irregularity is difficult to meet in low head machines. The two first limitations have been addressed by Jonsson [3]. Under well controlled laboratory conditions, Jonsson was able to measure the flow rate with an accuracy below 1% for L=3 m and U=2.4 m/s, i.e., UL=7.2 m^2/s, well below 50 m^2/s.

Hydro-Quebec has been developing the pressure time method for decades. Hydro Quebec has performed measurements in low head machines with the pressure time method outside the IEC41 standard. Levesque [4] presented result of a 24 m low head machine with a flow rate of 280 m^3/s. The distance between both sections was 9.4 m and UL=24 m^2/s. A large number (94) of current meters were used for comparison. A difference of 0.8% was obtained between both methods.

Hydro-Quebec has summarized its experience with the pressure time method in a recent article [5]. A feasibility diagram was presented, see Fig. 5.1.2. The diagram allows determining if the measuring conditions are favourable for the pressure time method. Furthermore, they have developed a method to evaluate the flow rate for similar groups at a power plant. The method is known has the *separate diagram method pressure-time* (SDPT). In this method, a transducer is used at the inlet of the turbine and another submersible sensor in the penstock inlet. As the pipe factor (L/A) is unknown, it is determined from an absolute flow measurements, usually the pressure-time method. More details may be found in Lamy and Néron [6].

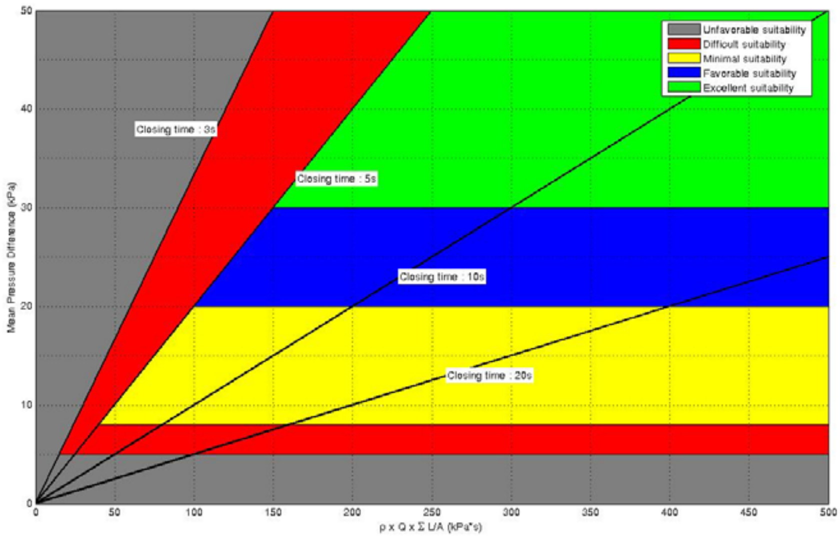


Fig. 5.1.2 – Guide for evaluating the applicability of the pressure-time method, Proulx and Bouchard Dostie [5].

Overall, the limitations of the pressure-time method were settled some decades ago. Sensor and computer technology have considerably evolved during this time. There is a strong necessity to study the IEC41 constraints and update them to the actual technology. Furthermore, the advances of numerical simulations allow deeper understanding of specific flow phenomena and thus method development.

5.1.4 Error Analysis

A comparative test performed by Hydro-Quebec between the pressure-time method and reference methods show that the uncertainty with a confidence of 95% can be assumed to be lower than ±1% and probably lower than ±0.5% in very favourable conditions, refer to Fig. 5.1.2. The uncertainty may rise to ±1.7% under unfavourable conditions.

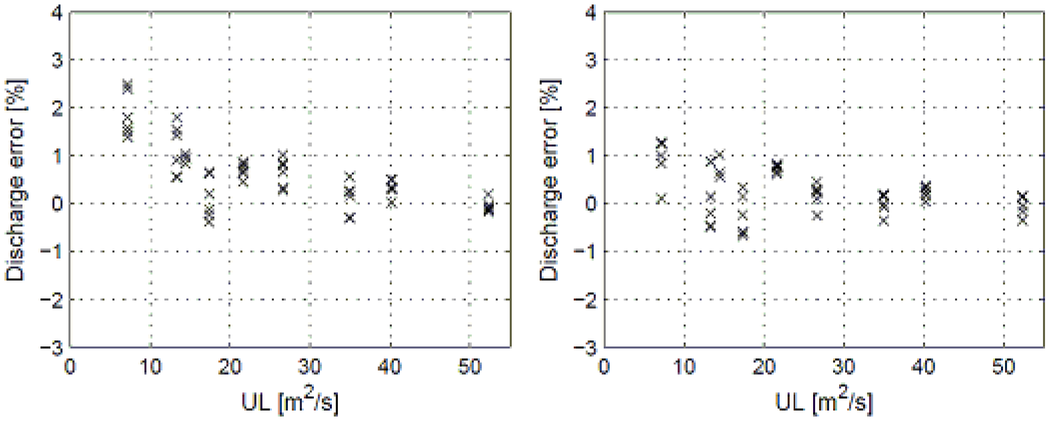
5.1.5 Cost and downtime for hydropower unit

The pressure-time method cost is similar to that of the Winter-Kennedy method if the pressure taps already exist and the cross-sections have been measured, i.e., ~200 kSEK. Furthermore, the production downtime is limited. Otherwise, the pressure taps installation and cross-sections measurements may be performed during a planned maintenance operation.

5.1.6 Further Development

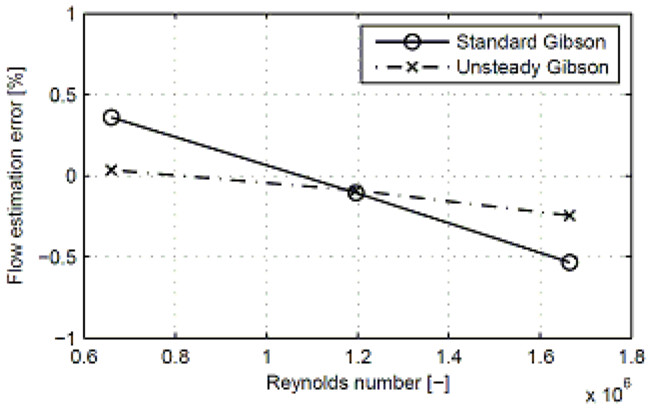
The IEC41 standard is being updated. The pressure-time method is expected to have new constraints. The minimum distance between the 2 sections will certainly be decreased from 10 to 8 m and thus UL from 50 to 40 m^2/s. The decrease of the distance between both sections is attributed to the development of the pressure sensors and computers.

Work on the development of the pressure-time method has been limited during the last decades. Adamkowski and Janicki [7] proposed a new upper integration limit compared to IEC41. Since some years, work on the method has also been performed at Luleå University of Technology, Sweden, for application to low head machines with encouraging results, Jonsson [3]. Focus has been on UL limitations. The study was made in a laboratory at the Norwegian University of Science and Technology (NTNU) under well controlled conditions. Flow measurements with an accuracy below 1% for UL=7.2 m^2/s (L=3 m and U=2.4 m/s) was achieved, see Fig 5.1.3. Jonsson developed also a new procedure taking into account the effects of unsteadiness to determine the discharge. The new procedure allows further decreasing the overall error by up to 0.4% points, see Fig. 5.1.4.

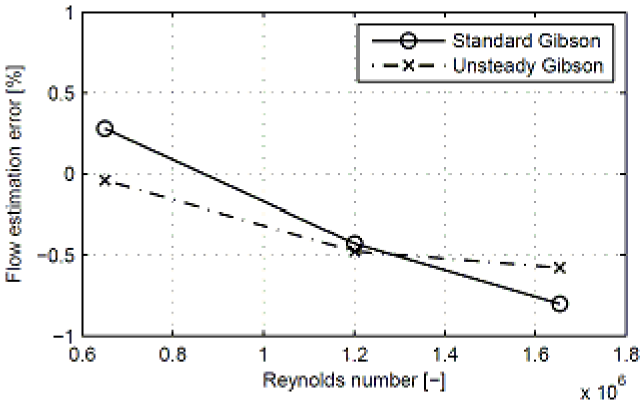


(a) Absolute sensors (b) Differential sensors

Fig 5.1.3 – Discharge error for different UL, Jonsson [3].



a)



b)

Fig 5.1.4 – Flow estimation error for a measuring length of L=6 m (a) and L=3 m (b), Jonsson [3].

Jonsson's developments were validated in laboratory with a small pipe diameter (D=0.3 m) and Reynolds number compared to large low head hydropower plants usually found in Sweden. Hydropower plants validation of the proposed unsteady pressure-time method is thus necessary in well-defined and controlled conditions. Measurements at Porjus U9 have newly been performed (August 2012) and are under evaluation.

Determination of the viscous losses during guide vanes closure is essential to determine the flow accurately, especially if the closure cannot be performed fast. Decelerating flows have received little attention. The losses in decelerating flows are not fully understood and need further attention [8]. Wall shear stress together with the velocity field and pressure are key parameters to measure simultaneously. They may allow further development of the numerical models. At least 2 dimensional numerical models are necessary to capture correctly the velocity profiles, which may present regions with opposite directions. The main goal in such work may be to considerably lower the minimum UL and variable cross-sectional area with a satisfactory accuracy for application to low head machines.

Low head hydropower plants have short intakes, which may not be straight. The pressure-time method has mainly been used for straight sections. Converging sections may be investigated in order to determine the applicability of the pressure-time method as well as necessary modifications. Furthermore, the method developed by Hydro-Quebec, SDPT, may be evaluated for low head machines and eventually further developed. All turbines have pressure taps at the turbine inlet, which may be used. As the pipe factor is unknown under SDPT measurements, the method may at least be used as a relative method. As the method may be used as a relative method, accurate determination of the viscous losses during the guide vanes closure is not important as long as the evaluation is performed similarly between the different measurements. Measurements evaluating the pressure-time method as a relative method at Porjus U9 have newly been performed and are under evaluation.

5.1.7 References

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5.2 Ultrasound Method

Ultrasound methods are emerging as good alternatives for flow rate measurements in low head machines. New methods appeared during the last decades. Three types of methods are today available:

- Transit time or time of flight (based on the sound velocity in the fluid),
- Acoustic scintillation or cross-correlation (determine the velocities of eddies in the fluid),
- Doppler (determine the velocity of single particles in the fluid).

The transit time method has been available since the end of the 60s; the first system was installed in 1968. The method was accepted in the IEC41 in 1991 as an optional, not primary, measuring method. The transit time method is expected to be a primary method in the revised IEC41 standard, which should appear in 1-2 years, i.e., 2013-2014. The acoustic scintillation method application to hydropower dates from the mid-90s, Lemon [1]. The method has evolved with time allowing a better accuracy, Lemon et al. [2]. The scintillation method was part of the Kootenay blind comparison test comparing methods for measuring flow suitable for use in short converging intakes, Taylor et al. [3], where transit time and current meter were also used. The application of the Doppler method applied to hydropower started also in the mid-90s.

5.2.1 Theory

5.2.1.1 Transit time

The transit time method is based on the fact that a pulse sound velocity in a medium is modified by the medium velocity, i.e., a pulse of sound travelling diagonally across the flow in a downstream direction will be accelerated and vice versa. The necessary time for a pulse to travel a distance L is given by:

$$T = \frac{L}{C \pm V \cdot \cos(\theta)}$$

C is the speed of sound in the medium, V the velocity of the medium and θ the angle between the acoustic path and the direction of water flow. The sign + is used for a pulse travelling in the downstream direction. Assuming 2 transducers separated by a distance L doing an angle θ with the flow (see Fig. 5.2.1), the upstream (T_1) and downstream (T_2) travelling time of the acoustic pulse between transducer A and B are given by:

$$T_1 = \frac{L}{C - V \cdot \cos(\theta)} \qquad T_2 = \frac{L}{C + V \cdot \cos(\theta)}$$

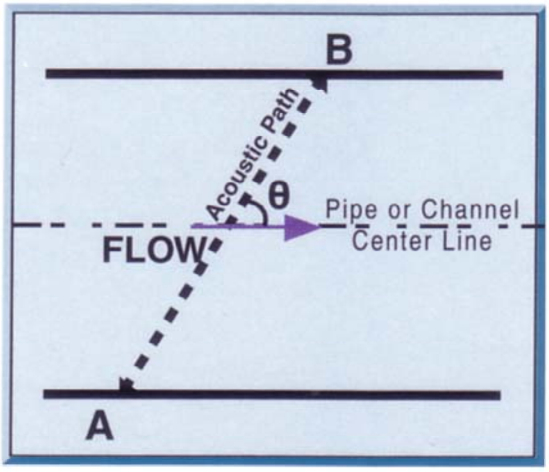

Fig 5.2.1 Transit time method acoustic layout, Accusonic [4].

The medium velocity may be obtained by rearranging the above 2 equations to yield:

$$V = \frac{T_1 - T_2}{T_1 \times T_2} \times \frac{L}{2 \cdot \cos(\theta)}$$

The average velocity of the medium over the acoustic path may therefore be determined knowing the distance between both transducers, the time of flight T_1 and T_2 and the angle θ with the flow.

For application to hydropower, several paths are used. The number of paths is a function of the geometry, where more complex geometries require a larger number of paths. For pipes having 10 diameters before the measuring section, 4 pair of transducers is sufficient. As much as 18 paths have been used, Walsh [5]. The flow rate Q is obtained after integration such as:

$$Q = \pi \cdot R^2 \cdot \sum_{i=1}^{N} (w_i \cdot V_i)$$

where R is the pipe radius, w_i a normalized integration weighting constant for the i^{th} path (defined by the path location) and V_i the velocity determined at the i^{th} path. The number of paths may be 1, 2, 4, 8 or 18.

5.2.1.2 Acoustic scintillation

The acoustic scintillation method is based on the perturbations of a sound pulse by the turbulent structures present in the flow [2]. Figure 5.2.2 presents schematically a layout. Two transducer/receiver paths are considered. The acoustic paths are sufficiently close (Δx), so the turbulence may be assumed to remain similar between both paths with a time delay Δt. The time delay is obtained from a cross-correlation of both signals. The mean velocity perpendicular to the paths is $V=\Delta x/\Delta t$.

The use of three transmitter/receiver paths at each level allows the determination of the velocity magnitude and angle. Usually, 10 paths are used.

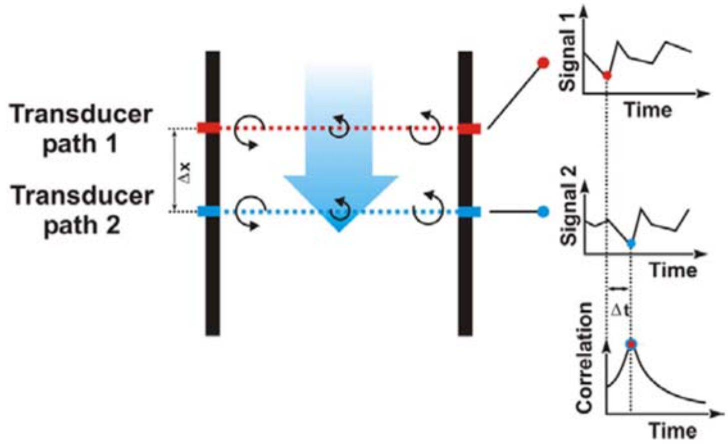

Fig 5.2.2 – Acoustic scintillation schematic principle [2].

5.2.1.3 Doppler

As a sound wave is emitted from a moving source and reflected by a moving particle, the reflected wave will, because of the Doppler Effect, be different from the incident wave frequency. This principle is used to determine flow in hydraulic turbines, where stationary sound sources are used together with the particles present in the water. In this case, there are actually two Doppler shifts.

A sound wave of frequency f, wave length λ and velocity $V_{sound}=f\cdot\lambda$ emitted by a stationary source and a particle moving toward the source with a velocity $V_{particle}$ are assumed. The speed of the wave crests is $V_{sound}+V_{particle}$ relative to the particle. The frequency f' detected by the particle is:

$$f'=\frac{V_{sound}+V_{particle}}{\lambda}=\left(1+\frac{V_{particle}}{V_{sound}}\right)f$$

The frequency "emitted" by the particle is:

$$f''=\frac{f'}{\left(1-\frac{V_{particle}}{V_{sound}}\right)}=\left(\frac{V_{sound}+V_{particle}}{V_{sound}-V_{particle}}\right)f$$

A particle moving away from the source induces a negative sign in the above relation. The particle velocity is then obtained:

$$V_{particle} = \left(\frac{\Delta f}{2f + \Delta f} \right) \cdot V_{sound}$$

5.2.2 Measuring Procedure

5.2.2.1 Transit time

The transit time method needs several paths to take into account the non-uniformity of the velocity profile. Low head machines necessitate therefore a large number of paths in order to achieve an acceptable uncertainty. At the Kootenay comparison test, Taylor [3], 18 paths were used in the non-uniform transition section, while 8 paths were used further downstream in the circular reference section.

The measuring section should be chosen as far as possible from any disturbances. Several path planes may be used to compensate for upstream disturbances leading to secondary flows. Four path planes should compensate for most of the secondary flow, IEC41 [6]. Low velocity (<1.5 m/s) and small diameter conduit (<0.8 m) should be avoided.

Accurate positions of the transducer and measurements are necessary as well as the dimensions of the conduit and path angle. Optical methods are available to this purpose.

5.2.2.2 Acoustic scintillation

Similarly to the transit time method, several paths are needed with the scintillation method, see Fig. 5.2.3. The different sensors are installed on a frame which is submerged at the intake, i.e., intake dewatering is not necessary. The use of 3 transmitter/receiver at each path allows determining the flow angle. Usually 10 paths are used per bay. Up to 30 paths can be installed, Lemon et al. [2].

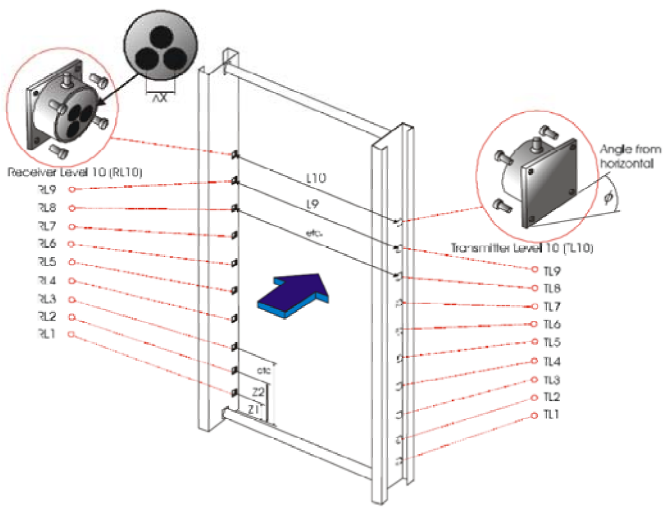

Fig 5.2.3 – Frame and sensors used with the scintillation method, Lemon and Lampa [8].

5.2.2.3 Doppler

Acoustic current Doppler profiler (ADCP) are widely use in open channel, Gandhi et al. [10]. Such method was newly introduced for measurements in low head machine. Sensors are installed to determine the velocity of particles in the water. The configuration is similar to the scintillation method, see Fig. 5.2.4.

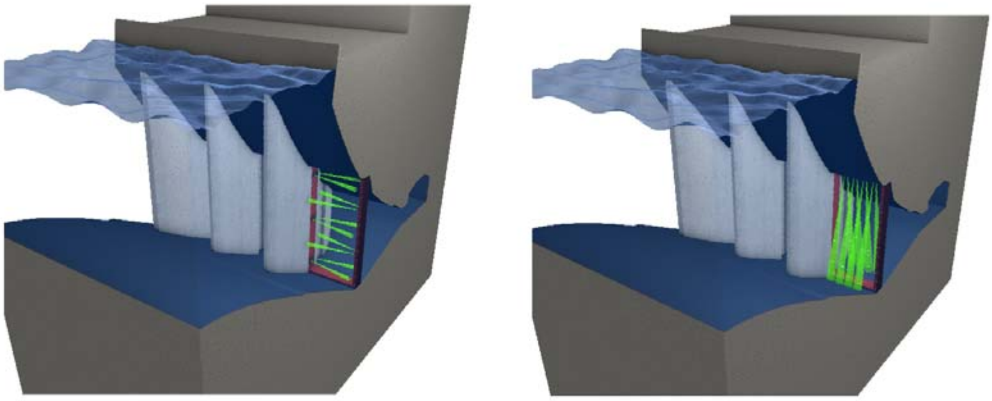

Fig 5.2.4 – Horizontal and vertical configuration of a Doppler system, Skripalle [9].

5.2.3 Problems Encountered

5.2.3.1 Transit time

Some of the problems encountered are: accurate determination of the area and attachment of the sensors to the water ways needing extensive installation.

5.2.3.2 Acoustic scintillation

There is no experience of the method in Sweden.

5.2.3.3 Doppler

There is no experience of the method in Sweden.

5.2.4 Error Analysis

5.2.4.1 Transit time

The company Accusonic has done a detailed error analysis and concluded that the flow rate may be measured with an accuracy of ±0.5% with the transit time method [7]. The measurements should be performed with a 4 paths flow system installed after a minimum of 10 diameter of straight pipe.

The transit time method was tested at the Kootenay canal in a low head simulation using 18 paths, Taylor et al. [3]. The difference with the reference measurement, transit time in a straight pipe further downstream, was below 0.1% and a scatter of 0.15% with a 95% population confidence interval. The uncertainty of the flow rate measured was estimated to be within ±1%.

The method is recognized as mature and will be a primary method in the updated IEC41 standard.

5.2.4.2 Acoustic scintillation

The scintillation method is still being developed for improved accuracy, Lemon et al. [2]; most of the effort focuses on the algorithm. The method was newly tested at the Kootenay canal in a blind test. A deviation of 0.5% with the reference method, transit time, was found.

The method will be proposed as an optional method in the updated IEC41 standard.

5.2.4.3 Doppler

The use of ADCP to determine flow rate in a plant with sensors mounted on the wall is relatively new. The work presented by Skripalle [9] did not include any error analysis in the field. No systematic error analyses were either found in the literature.

Standard ADCP sensors used in river measurements have usually accuracy in the range 0.5-1% (http://www.rdinstruments.com). A comparative measurements between ADCP and an acoustic Doppler probe shown close agreement, Staubli et al. [11]

5.2.5 Cost

The cost associated with ultrasonic methods is high. The sensors together with the related electronic and associated software have a prohibitive price compared to other method such as the Pressure time method, which require pressure sensors and a data acquisition system. Furthermore, the production may have to be shut down for sensors installation, which constitutes the major cost.

5.2.6 Further Development

The ultrasound methods presented in the paragraph are developed by companies keen to have their method accepted as primary method for the standards available; e.g. IEC and ASME. The transit time method will be proposed as a primary method in the upcoming IEC41 standard, while the scintillation method will be proposed as an optional method. No information is available on the Doppler method.

The results of the Kootenay canal point out the suitability of the transit time method for flow measurements in low head machines. The scintillation and Doppler method may need further development to be performed by the companies.

Universities and power plants owners may help in such development by developing comparative test as done at the Kootenay canal, Taylor et al. [3].

5.2.6 References

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5.3 Current Meter Method

The current meter method is an absolute velocity-area method which also can provide information about the flow pattern. It is recognised as an absolute method by the IEC41 standard for field acceptance tests of hydraulic performance tests [1]. The method in general is also described in ISO 3354 [2] and SS-EN ISO 748:2007 [3]. The overall uncertainty at a 95% confidence interval should be in the range of ±1 to 2.3%, with variations for different cross-sections and systems, for a correct set-up of the measurement method.

The following text is structured as the previous chapters; theory, measuring procedure, problem encountered, error analysis and further development.

5.3.1 Theory

The current-meter method determines the discharge by integrating the local velocity measured at a set of propeller-type meters placed over a cross-section, e.g., in a channel. In general, the cross-section is divided into a number of vertical segments and for each segment the width, depth and mean flow velocity is measured. The mean flow velocity is determined by point velocity measurements carried out with current-meters at different depths in the section.

The discharge, Q, is then determined by:

$$Q = \sum_{i=1}^{m} b_i \cdot d_i \cdot V_i$$

where m, b_i, d_i, and V_i are the total number of segments at the cross-section, the width, the depth and the mean velocity of each segment *i*, respectively.

There are several methods to determine the mean velocity in each segment for different types of cross-sectional areas; velocity distribution method, reduced point method, integration method. There are also several methods to compute the discharge; graphical method, arithmetic method, independent vertical method and horizontal plane method for example. Description of these methods can be found in [2, 3].

5.3.2 Measuring Procedure

The velocity in an open channel or closed conduit in a hydropower unit can be determined by inserting current-meters into the flow. The rotational speed of the current-meter corresponds to a flow velocity. The relation between rotational speed and velocity is obtained from the manufacturer or after calibration. The integrated water velocity over the cross-sectional area thus gives the discharge as described in 5.3.1. There are 2 alternatives; current-meters positioned at specific points across the section to be investigated or fixed on a rack, which is traversed across the cross-section. The second alternative requires fewer current-meters but more advanced equipment as the meters must be moved at constant speed and also must be less sensitive to vibrations. If one current meter is used for each segment, the discharge can instantaneously be computed.

There are several requirements for the method to be applicable to hydraulic turbines according to the standard:

- Only propeller type current-meters are allowed according to the IEC41 standard [1].
- The measurement period must be long enough to include variations in the flow velocity (minimum 2 min).
- The number of current-meters must be “sufficient” to determine the velocity profile over the segment. For a circular penstock a minimum of 13 current-meters must be used and for a rectangular or trapezoidal section at least 25 current-meters must be used for both open and closed conduits.
- The number of current-meters and assembly of rods must not be “too large” to cause blocking of the flow.
- The current-meters and the rods must be mounted stiff to avoid vibrations during measurements.
- Some reference of the velocities and the flow pattern must be known a priori determination of the type and size of the current-meters, the sampling time and the position of the meters near the bottom, surface and walls of the cross-section.
- The water quality must be good; dirt sticking to the current-meters should be avoided.
- Calibration of the current-meters must be made using the same supporting rod structure and the distance between the meters cannot change between calibration and test.
- Open channels must have well-defined cross-sectional areas and natural cross-sections are not allowed for this methods.

5.3.3 Problems Encountered

There are several problems that are associated with the current-meter method:

- Installation can be both costly and time consuming.
- Blocking of flow by the assembly rods and the current-meters is possible; some interference of the flow is always present due to the nature of the installation.
- Unstable and/or skewed flow causes large variations and unfavourable measurement conditions for the calibrated current-meters. This can also cause unpredictable vibrations of the measurement row/rack.
- Wind induced disturbances in open channel flows induce errors to measurement.

- Choice of appropriate current-meter range may be difficult for unknown flow pattern.
- Suspended material in the flow can accumulate at the current-meters over time and induce errors in the measurements, see Fig. 5.3.1.

Currently, there is no standard available for the use of current-meters in short penstocks where the length of the penstock over its diameter is below 25. This limitation covers a very large amount of the hydraulic machines in Sweden. Instabilities, swirl, secondary flows and skewness may occur due to short converging sections. If possible straightening devices such as bell-mouthed nozzles should then be mounted to give a more stable, straight flow. The drawbacks with such nozzles are that the installation is both costly- and time consuming. Effects on the actual performance of the unit can also occur due to modifications in the intake. There are also special measurement methods for such cases, which aims at determining the angle of the flow to best align the current-meters with the flow.

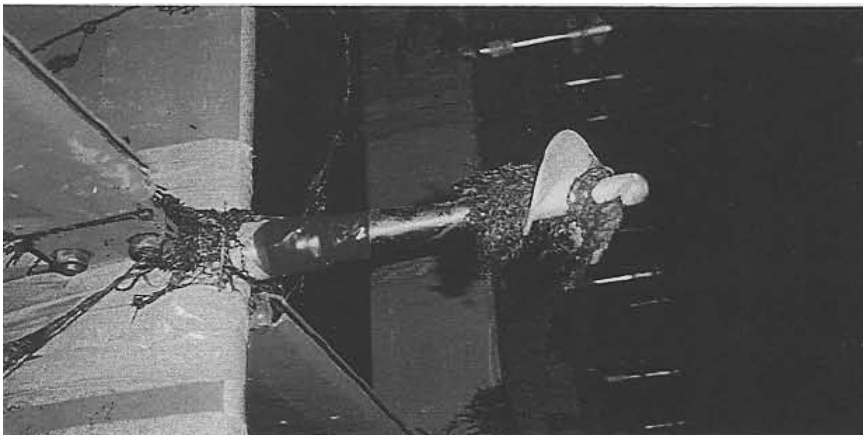

Fig 5.3.1 - Grass caught in current-meter after tests.

5.3.4 Error Analysis

Regarding the uncertainty of the method, the IEC41 standard [1] stipulates that the estimated systematic uncertainty at 95% confidence interval should be between ±1 to 2.3%.

The reported uncertainty from the industry using the method for hydraulic turbines is ±1-1.5%.

5.3.5 Cost and downtime for hydropower unit

Mounting fix frames, scaffoldings, rods and current meters is time consuming. The downtime for the hydraulic machine is of the order of 2 weeks, this include; installation of the equipment, measurement and disassemble. If direct integration method is used, i.e., the current meters are traversed across the section, the downtime is less. The current meters must also be maintained periodically and cannot be deployed for too long due to the risk of debris interfering with the meters.

5.3.6 Further Development

There is currently no standard for the method for low head hydro power units with short intake in Sweden. The uncertainty in the method becomes too large under these unfavourable measurement conditions, which associated to the necessary downtime, makes such method inadequate.

5.3.7 References

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5.4 Dilution Method

There exist two basic tracer dilution methods for determining the flow rate in a given application. In both methods radioactive and non-radioactive tracers can be used. Both of them are mentioned in the IEC 60041 standard [1]. The IEC standard recommends using the constant rate method instead of the integration method. This is due to the practical difficulties of the integration method such as weighting the exact amount of tracer injected into the main flow, finding the exact volume between the injection point and the sampling point etc. The constant rate method is the only method described in the following. Flow measurement using the tracer dilution method has been proven to be an accurate, low cost and adaptable method in areas such as metering of feed water flow in nuclear power plants and on-site calibration method within the process industry [2]. The method is also valid for hydro power plant applications, Cyrenne and Eng [3]. There are several advantages (accurate, low cost etc.) with using the tracer method for stream flow measurements, Moore [4]. The tracer dilution method has been successfully used for flow measurement in hydroelectric stations where other methods were not feasible [5]. In addition, this method is suitable to use in power plants where it is not allowed to significantly affect the operation schedules by an efficiency test, Gutierrez and Alberto [6].

The estimated overall uncertainty at a 95% confidence interval should be in the range of ±0.5 to 3.0%, with variations function of the system, set-up of the measurement method, mixing length etc.

The following text is structured as the previous chapters; theory, measuring procedure, problem encountered, error analysis and further development. The subsequent section is focusing only on the constant rate method since recommended in the IEC 60041.

5.4.1 Theory

The constant rate method is based on the following principle. A tracer with known concentration C_1 is continuously injected into the flow system of study. At a point downstream, the concentration C_2 is measured. The flow rate Q can then be determined from the following relation:

$$Q = Q_1 \cdot \frac{C_1 - C_2}{C_2 - C_0}$$

where Q_1 is the flow rate of the injected tracer and C_0 is the background concentration of the injected tracer, i.e., the concentration upstream the injection point. An advantage of this method is that the geometric characteristics of the pipe may not need to be known.

Apart from technical challenges it is also important to consider other stakeholders that may have interest in how tracers are used/distributed in hydropower plants, such as local authorities, environmental organisations and the public.

5.4.2 Measuring Procedure

The dilution methods in general are described in ISO 2975 part I-III [7] and ISO 9555 [8]. ISO 2975 covers flow measurement using the tracer methods in closed conduit and ISO 9555 flow measurement with the tracer method in open channels. This section describes the general details of the constant rate method. One main task in this method is the choice of an appropriate tracer. There are plenty of tracers available but the tracer must comply with the following considerations:

- easy to mix in water
- detectable at concentrations lower than the highest permissible concentration while taking into account toxicity, corrosion etc.
- have only negligible influence on the flow rate
- inexpensive if possible
- does not react with the water or any other substance in the water in such a way that it affects the measurement
- be analysed accurately at a low concentration

Even with these specifications, there are several tracers available. Once an appropriate tracer, usually a salt, dye or radioactive isotope, is chosen the measurement will be performed as illustrated in Fig. 5.4.1. The tracer with known concentration C_1 is continuously injected into the pipe system. The flow rate of the injected tracer Q_1 is measured continuously. At a point far downstream from the injection point, the concentration C_2 is measured. The sampling point must be far enough from the injection to ensure mixing. Ideally the background or initial concentration C_0 of the injected is zero in the main flow but this is not always the case. To reduce the measurement uncertainty of the method it is necessary to measure the initial concentration of the tracer in the main flow upstream of the injection point, as illustrated in Fig. 5.4.1.

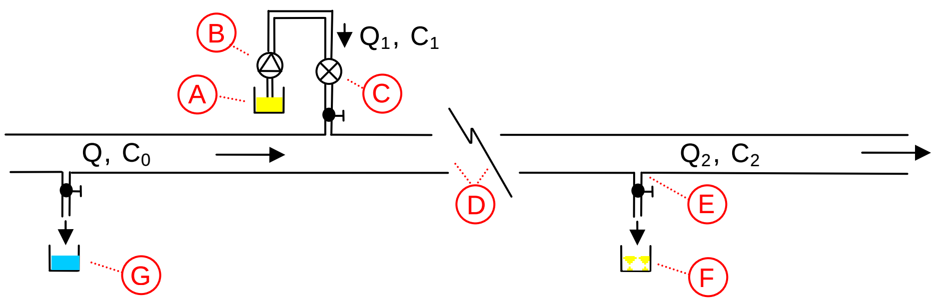

Fig 5.4.1 - Schematic drawing of the constant rate dilution method.

The searched flow rate Q can be determined using the following equation:

$$Q = Q_1 \cdot \frac{C_1 - C_2}{C_2 - C_0}$$

If C_1 is much larger than C_2 and C_2 much larger than C_0, the above equation reduces to:

$$Q = Q_1 \cdot \frac{C_1}{C_2}$$

A schematic figure of the concentration C2 as function of time for the constant rate dilution method is presented in Figure 5.4.2. The injection starts at time=0 min. As some time, the concentration C2 reached a steady-state. The average value of the steady-state over usually 3-5 minutes measurement is used and put in the first and second equation. The time before the increase of the concentration C2 depends on the distance between the injection and mixing point and the flow rate. In figure 5.4.2 this time is 5 minutes.

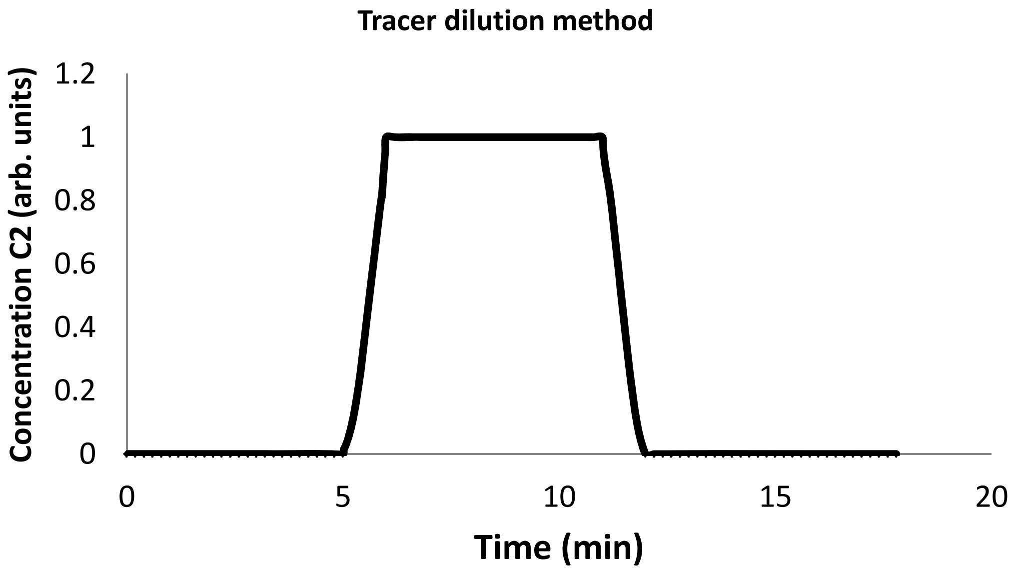

Figure 5.4.2 - Schematic drawing of a measurement for the concentration C2 as a function of time using the constant rate dilution method.

5.4.3 Problems Encountered

There are several issues that need to be considered when using the constant rate dilution method.

First of all, the tracer itself is important. Some tracers can be temperature dependent; in those cases the injected solution must have the same temperature as the diluted solution at the sampling point [3, 4].

Furthermore, there must be no leakage or inflow between the flow measurement at point C in Fig. 5.4.1 and the sampling point.

Another critical parameter is the mixing length. In ISO 2975 a theoretical derivation of the mixing length can be found. Three different equations are derived and all of them conclude that a mixing length of L/D>100 should be sufficient to obtain a concentration variation less than 0.3% across the pipe cross section. This assumption is valid for a Reynolds number of $Re=10^5$ ($Re=UD/\nu$, where U, D and ν are the mean velocity, hydraulic diameter and kinematic viscosity of the fluid) and the tracers must be injected in the centre of the pipe. By increasing the Reynolds number to 10^6 the mixing distance increases by the order of 20-25%. However, the standard recommends using these values with caution. Experiments have shown that the mixing length can be at least two times larger but also smaller depending on a lot of different parameters. One example, if the injection is performed by a single hole at the pipe wall instead of four holes around the pipe wall the mixing length is increased from around L/D>90 to L/D>200 [7]. Since a homogenous mixing of the tracer in the water is desired at the sampling point it is highly recommended that the pipe system between the injection and sampling point contains bends and other components, which disturb the flow profile and increase the mixing.

Low head hydraulic machines represent thus a challenge for the dilution method as the distance between inlet and outlet L/D are well below 100. The actual experience is in fact very limited. The ISO 2975 states that a turbine contributes to a mixing length of around 100 pipe diameters, but this need to be verified.

5.4.4 Error Analysis

There are several sources of uncertainties in a dilution flow measurement. Each of them gives its contribution to the overall measurement uncertainty. The different contributions are marked from A to G in Fig. 5.4.1. Both quality and homogeneity of the tracer (A in Fig. 5.4.1) contributes to the uncertainty. The pump (B in Fig. 5.4.1) and pipe to the injection point need to be considered. The method assumes no leakage or inflows of the injected tracer between the flow measurements in point C and the sampling point E. Any leakage or inflow influences the uncertainty. Both the flow meter at point C and the instrument for the concentration measurement at the sampling point F contributes with its uncertainty to the overall uncertainty. Since it might not be a homogenous mixture at the sampling point, the location of the concentration measurement E might be critical and makes a contribution to the total uncertainty. If the constant rate dilution method is performed according to the standard [7, 8], the total uncertainty at a 95% confidence level can reach a value of 0.5%. However, uncertainties with a value of around 1-3% are more typical in practice [1-6].

5.4.5 Cost and downtime for hydropower unit

The cost and downtime associated with the dilution method for measurements on low head hydraulic machines is today unknown as the method has not been specifically tested to this purpose. However, a single measurement with the tracer dilution method usually takes around 5-15 min depending on the flow rate, required mixing length etc. [3-6]. This gives an estimated cost in the order of 200 kSEK.

Assuming the tracer can be injected at the inlet of the penstock and the concentration measured on the wall of the draft tube, i.e., a perfect mixing is achieved, such measurements should not perturb production. The necessary tubes or/and taps in the draft tube may be installed during a planned maintenance.

5.4.6 Further Development

As mentioned above there are some measurement difficulties with the dilution method. SP Technical Research Institute of Sweden have applied for an EU-project with the goal to validate the constant rate method for hydro power plant with low head. One key for low measurement uncertainty using the constant rate method is a well-mixed tracer with the flow at the sampling point. There are two related issues to achieve good mixing that will be studied, the injection technique and the mixing length. If a method can be developed ensuring good mixing already at the inlet, the mixing length can be reduced. In addition, the suggested mixing lengths given in the ISO 2975 still need to be validated experimentally. The choice of tracer needs to be decided. The amount of tracer needed for a measurement in a hydro power plant should be reasonable. For example, the tracer Rhodamine requires a concentration of 5-100 ppb at the sampling point. With a concentration of 100 ppb and an average water flow rate value of 340 m^3/s, this corresponds to around 34 ml/s of Rhodamine. The first part of the project will focus on the development of the injection method under laboratory conditions. Full-scale tests will thereafter be performed.

5.4.7 References

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5.5 Volumetric Method

The basic principle of the volumetric method consists in running a turbine at a constant load during a long period of time, about a day. The flow rate through the turbine is determined by determining the volume change in the reservoirs by measuring the level of the head and tail water and the reservoirs area. This method was mainly use some decades ago. The method is attractive since there is no need to shut down the station for geometrical measurements or sensor installations and there is no need to install obstacles in the waterways which might disturb the flow. Also this method does not suffer from potentially changing measurement conditions such as renovated waterways, changed surface conditions, refurbished pressure taps etc. Because of these favourable properties new interest in the method is initiated.

There are two methods available when performing a volumetric flow measurement. One is absolute and the other is relative. In both cases the hydropower plant is operated at a constant load during a long period of time, ranging from a few hours up to one or more days. The absolute method is accepted in the IEC41 [1] standard whilst the relative method is not mentioned in that text. In an artificial basin the uncertainty at the 95% confidence interval ranges from ±1 to ±2% [1], no information about the uncertainty is given for natural basins.

5.5.1 Theory

Absolute method

When performing a discharge measurement with the volumetric method the upstream station should be shut down while the turbine of interest is operated at a constant load. The method is similar to a bucket method, Cengel and Cimbala [2], that is, the mean net flow rate, $\overline{Q}_{net}$, is obtained from the change of the reservoir volume, *ΔV*, during a time period, *Δt*:

$$\overline{Q}_{net} = \overline{\mathrm{Q}}_{\mathrm{s}} + \overline{\mathrm{Q}}_{\mathrm{u}} + \overline{\mathrm{Q}}_{\mathrm{t}} + \overline{\mathrm{Q}}_{\mathrm{l}} = \frac{\Delta \mathrm{V}}{\Delta t} \qquad (1)$$

where the bar denotes a mean value. The term $\overline{Q}_{net}$ is comprised of four terms; $\overline{Q}_s$ the flow rate which is of interest to measure, $\overline{Q}_u$ the leakage flow from the upstream station, $\overline{Q}_t$ the water entering the basin through rivers, creeks and by rainfall whilst $\overline{Q}_l$ is the leakage through the intake or guide vanes of neighbouring turbines. Equation (1) gives the mean flow rate during the test period. However, since the head of the plant changes during a test the flow rate is also affected. The instantaneous flow rate, $Q_s(t)$, during an arbitrary session of the measurement is given by the following equation [3]:

$$Q_s(t) = Q_{0s}\sqrt{\frac{H(t)}{H_0}} \qquad (2)$$

Where Q_{0s} is the flow rate at the start of the test with corresponding head H_0 and $H(t)$ is the head at time t. As the time interval Δt goes to zero, a generalization implies that the instantaneous flow rate, $Q_{net}(t)$, is given by:

$$Q_{net}(t) = Q_s(t) + Q_u(t) + Q_t(t) + Q_l(t) = \frac{dV}{dt} \qquad (3)$$

where $Q_s(t)$, $Q_u(t)$, $Q_t(t)$ and $Q_l(t)$ are the instantaneous values of the above defined variables and dV/dt is the instantaneous rate of change of volume. After integration of the above equation and using equation (2), the flow rate at any time of a test is obtained from:

$$Q_s(t) = \frac{\Delta V - \int_{t_{start}}^{t_{end}} \left[Q_u(t) + Q_t(t) + Q_l(t)\right] dt}{\int_{t_{start}}^{t_{end}} \sqrt{H(t)}\, dt} \sqrt{H(t)} \qquad (4)$$

where t_{end} and t_{start} are the end- and start time of the measurement. This calculation may be performed after the measurement has completed since it requires the change in volume, ΔV, during the test period as well as integration over the test period. According to IEC41 [1], the head should not vary more than 1% during a run. This condition incorporated in equation (2) shows that the flow rate varies within 0.5% during a run.

Relative method

The volumetric method used as a relative method is based on measuring the flow rate relative to an upstream station having a known flow rate. The station(s) of interest should be operated at a constant load and any change in the basin water level indicates a difference in flow between the station(s) of study. The difference in flow rate is calculated in a way similar to equation (1). A volume change in the basin during the measurement period gives the flow rate difference. This method is not limited to 2 stations; previous work has involved 3 stations, unfortunately the results were not published.

5.5.2 Measuring Procedure

Absolute method

According to IEC41 [1] the following points should be considered when performing a measurement with the volumetric method:

- The volume as a function of water level should be determined and analysed. The measurement should be confined in the water level range where this function is simplest in shape.

- The measurement should be performed during a time period which enables the volume change to be determined within ±1%.
- The water level should be measured in at least 4 points simultaneously and if the basin is irregularly shaped this number should be increased sufficiently to achieve an average value representative for the mean water level.
- In order to check consistency of the results, calculations by equation (1) should be performed during intermediate states of the measurement.
- The measurement should be performed during a calm day, preferably during late autumn when the flow from rivers and creeks are at a minimum but before the basin freezes. In the case of strong wind or rainfall the measurement must be suspended. The definition of strong depends on the layout of the stations under consideration and must be considered independently for each occasion.

Furthermore, the following points must also be considered:

- The water level reading will be affected by noise; a least squares function should be fitted to the data in order to reduce the effect of these disturbances [4].
- When measuring the water level, care must be taken to the surface waves which might be present in the basin. These waves are termed seiches and their period time depends upon the topography of the basin. The recorded water level must be filtered to eliminate the effect of these seiches.

Relative method

The measuring procedure is similar to the absolute method. Water level measurements should be conducted at several points in the basin and the measurement should be performed during a sufficiently long time in order to determine the volume change accurately.

5.5.3 Problems Encountered

One problem which has been encountered is the lack of precision in determining the topography of basins. Examples exist where the volume as function of water level obtained from different sources deviates with as much as 6%. Another source of problem is the absorption in the bank in natural basins introducing errors in the determination of volume change. The forecasts and old statistics of water flow from rivers and creeks are based upon the reported discharges of the stations and the sizes of the basins; these are prone to errors which introduce further uncertainties in the flow rate determination.

5.5.4 Error Analysis

According to IEC41 [1], the uncertainty in an artificial basin at the 95% confidence level ranges from ±1 to ±2%. As mentioned earlier no information is available for natural basins. The principal sources of error in a volumetric measurement is the uncertainty in basin volume as function of height, the determination of water level change and the uncertainties in quantification of the leakage- and river/creek flow.

5.5.5 Cost and downtime for hydropower unit

Accurate water level sensors measuring simultaneously are necessary for such measurements. An accurate determination of the basin topography is necessary. Different methods exist with prices starting at around 30 kSEK for the simplest approach using photographs ranging up to a few 100 kSEK for a laser scan.

The main cost in performing such measurement may reside in the lost income due to eventual downtime of the upstream/downstream stations or non-optimal operation. This is of course dependent on the length of the test, the number of stations involved and the power production of undisturbed stations is. The time of the test should be performed according to the market to minimize production loss of the adjacent stations which should not be operating. Generally, night-time should be the most appropriate as the production then is generally at a minimum.

5.5.6 Further Development

More advanced methods to determine the topography of basins have been developed during the last years. Nowadays laser scanning from the air is an option and laser scanning from boats is under development. Photographs taken with airplanes have now a higher resolution compared to earlier which enables determining more accurately the basin area.

The devices for measuring water level are getting higher accuracy which reduces the uncertainties in determining the change in water volume. A method similar to the volumetric has been developed by Adamkowski et al. [5]. This was used to determine the cycle efficiency of pumped storage plants. However, since these plants are very rare in Sweden interest in this method is not of primary importance.

J. Sundström is currently evaluating the limitations of the volumetric method for his master thesis. A report will be available at www.ltu.se in the first half of 2013.

5.5.7 References

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6 Discussion & Recommendations

Three different ultrasound methods are now available. Their development is specific to companies. The Doppler method is certainly the method requiring the most development. The scintillation method will appear as an optional method in the updated IEC41 standard. The transit time method will become a primary method in the updated IEC41 standard. It is an absolute method. The measurements performed at the Kootenay canal point out the good accuracy of the transit time method for low head machines. The uncertainty of the flow rate measured was estimated to be within ±1%. The short and variable flow passages in low head machines necessitate the use of a large number of acoustic paths to get a good accuracy. Dewatering of the penstock may be necessary to install the acoustic sensors. The accumulated cost is much larger than the most widely used method in Sweden: the Winter-Kennedy method, which is a relative method. Nonetheless, the total cost for the transit time method of 1-2 MSEK should be compared to the method used today in Sweden to ensure a good accuracy; model test, which cost about 5 Mkr. In such a test, several characteristics of the machine are evaluated beside the efficiency such as cavitation, guide vanes torque, pressure pulsation and other.

Model tests allow efficient measurements in a well-controlled environment with a total uncertainty below 0.2%. Model geometrically similar to the prototype may be tested. Often the inner waterways of the model are homologous to the prototype. The cost is prohibitive. As the model and prototype are not dynamically similar, a scale-up formula is used to obtain the prototype efficiency from the model efficiency. Nevertheless, efficiency scale-up formulas are based on simplified assumptions, e.g., friction over a plate. Such type of efficiency scale-up has recently been updated to take into account the effect of roughness. Deviation between the effective prototype efficiency and scaled-up efficiency may arise due to variation in, e.g., inlet/outlet flow, geometrical variation, but also the assumptions made to derive the scale-up model(s). Assessment of the influence of the parameters differing from the model test and scale-up model(s) accuracy should be addressed. Porjus U9 prototype may be an adequate object as extensive model measurements have been performed on the corresponding model.

The Winter-Kennedy method is today the most widely used method to estimate the flow rate in Swedish low head hydraulic machines. Sometimes the Winter-Kennedy is used as an absolute method; or rather the results have been treated as absolute, while the method is relative. There is a need to further educate project leaders in companies on the method. As the consultants usually perform the Winter-Kennedy measurements, they may perform such a task. The main advantage of the Winter-Kennedy is its simplicity allowing a low cost: ~200 kSEK. Used for several decades, the method has shown in some cases the ability to produce unpredictable results. This possible variability in the results without clear explanations points out the lack of understanding in the method and its limitations. The method is e.g. usually used without controlling the pressure taps, a source of possible bias, due to cost and time constraints in a project. The IEC41 is specific on the matter: "*The pressure taps used shall comply with the dimensional requirements of 11.4.3. Since the differential pressures to be measured may be small, special attention should be given to removing surface irregularities*". Stainless steel should also be used at the pressure tap positions. Nicolle and Proulx [6] wrote a very interesting paper lifting some limitations of the method with the help of numerical simulations and experiments. The paper is freely available on the web at www.ighem.org. They point out the lack of scientific reason to have a variable exponent for the pressure: 0.48-0.52 according to the IEC41 as demonstrated in a previous paragraph: 4.1.1. According to the Navier-Stokes equation, it should be 0.5. Their simulations of a low head hydraulic machine with a semi-spiral casing show that the flow delivered to the stay vanes is unsymmetrical and its distribution varies as a function of the guide vanes opening leading to variation of the constant *K* multiplying the pressure variation across the spiral. The results are found highly sensible to inlet boundary conditions: variation up to 5.4% function of the configuration. There is a need for a systematic error analysis of the method. Furthermore, the evaluation of the results may differ from one consulting company to another one. A procedure/road book for implementation, evaluation and reporting should be written. Such document will give a common foundation to turbine owners, authorities, manufactures and consultants performing such measurements for discussion concerning the results. Work on a common guideline within the industry (SEK-TK4) has been drafted with the purpose of finding a common ground for best-practice within the industry to carry out the Winter-Kennedy measurements. Nonetheless, there is a need for alternatives to the Winter-Kennedy method. The use of an existing absolute method seems to be the more promising.

The pressure-time method is an absolute method. The experience with the method is limited in Sweden. It is attributed to the constraints of the method, see 5.1. Today, the experience with the method is too limited to determine the flow rate in low head machines with a low uncertainty. Developments are going on at Luleå University of Technology, Sweden, since some years in order to widen the application range of the method for application to low head turbines. The preliminary results are positive but validation work on prototype is needed. During autumn 2012, the method has been tested at the full-scale Research and Development facility Porjus U9. Shorter distance between the cross-sections (L=5 m, $12<UL<45$ m^2/s) and a new evaluation algorithm taking care of the transient flow phenomena (Jonsson [7]) are evaluated. The preliminary results are encouraging. The algorithm will also be assessed on a large number of measurements performed by Hydro-Quebec, Canada, on different prototypes. Beside these tests, a development of the method as a relative method will be tested. In the method, the pressure is only measured at one section. The pipe factor is unknown. As a relative method, an accurate determination of the losses is not necessary as long as they are determined similarly between the tests. One of the main advantages will be a larger pressure signal, compared to the Winter-Kennedy, expecting to give more reliable results but also less sensible as the entire penstock is considered.

Beside the planned activities, further development of the method is of interest as its operational cost is very attractive, similar to the costs of the Winter-Kennedy method. Variable cross-sectional areas are often present in low head machines inlet. Their effects on the pressure-time method should be systematically investigated for absolute and relative measurements. Wall shear stress, velocity field and pressure are key parameters to be measured simultaneously for detailed understanding of the physical phenomena and method development. They may allow further development of the numerical models. At least 2 dimensional numerical models are necessary to capture correctly the velocity profiles, which may present with opposite directions in the flow. The main goal in such work is to considerably lower the minimum UL with a satisfactory uncertainty for application to low head machine but also be able to determine accurately the friction losses. Accurate determination of the friction losses may allow decreasing the necessary pressure difference during closure between both sections. A decrease of minimum pressure difference between both sections allows an increase of the necessary time for guide vanes closure for such measurements and thus decreasing stress on the machine. Such measurements may also be performed with various geometries, e.g., contraction.

Several other methods have not received much attention during the last decade: current meter, dilution and volumetric methods.

The variable cross-sections in low head machines make the use of current meters difficult due to flow angles. Much time is also necessary for calibration and installation of sensors.

The dilution method is another method which has not been popular during the last decade. The development in increasing the accuracy of concentration measurements makes now such method attractive for low head machines. Nonetheless, several issues need to be addressed; injection technique, mixing and selection of tracer as well as environmental considerations. SP planned to perform measurement in laboratory during 2013. The object is to investigate the possibility to reduce the require mixing length and potential needs of the method for low head hydro power plants. Preliminary measurements are also planned at Porjus U9 prototype.

The volumetric method is another method requiring few installation efforts but necessitates running the machine at a certain load for a given period of time as well as shutting down the neighbourhood machines. The constraints to use this method are today unclear. A master thesis on the subject is actually going on; a collaboration between, EON, Vattenfall and LTU. The report should be available during the first half of 2013.

A table summarising the estimated development status and cost is presented, see Table 6.1. The working group suggests several actions. They are divided in 2 categories: long term and short term. The long term actions are typical SVC projects for PhD or/and senior researcher while short term actions are projects for consultant or/and senior researcher. The following actions are suggested in a hierarchical order:

Long term projects

1. Development of the pressure-time method as an absolute and relative method
2. Evaluation of scale-up formula and influence of the parameters differing between model and prototype such spiral inlet boundary conditions

Short term projects

1. Procedure/road book for implementation, evaluation and reporting of the Winter-Kennedy method. Continue working on the common guideline drafted in SEK-TK4.
2. Systematic error analysis of the Winter-Kennedy method
3. Testing of the volumetric method on a full-scale unit to investigate capabilities and evaluate necessary development for low head hydro power plants
4. Testing of the tracer dilution method on a full-scale unit to investigate capabilities and evaluate necessary development for low head hydro power plants

Table 6.1 – Measuring methods with estimated development status and cost

Method	**Type**	**Development status*[1]**	**Development status for low head*[2]**	**Estimated cost (kkr)**	**Estimated downtime in days[3]**
Winter-Kennedy	Relative	2	2	200	0[5]
Pressure time	Absolute	4	1	200	0[5]
Transit time	Absolute	5	3	1000	3
Scintillation	Absolute	3	2	1000	3
Doppler	Absolute	2	1	1000	3
Current meter	Absolute	5	5	1000	0
Dilution	Absolute	2	1	200	0
Volumetric	Absolute	1	1	200	1
Model test	Absolute/Model[4]	5	5	5000	0

*: scale of 1 to 5 use to grade (1: very low, 2: low, 3: average, 4: good, 5: very good)
[1]: development status in general independently of the head
[2]: development status for low head machines
[3]: estimated time perturbing production necessary to install rack, sensors and measure specific dimension
[4]: measurement are absolute on the model and thereafter scaled to prototype
[5]: assuming the pressure taps are available

7 References

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