A NEW METHOD FOR CONTINUOUS EFFICIENCY MEASUREMENT FOR HYDRAULIC TURBINES

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ABTRACT

Over the years, Hydro-Québec has developed solid expertise in efficiency measurements and computation fluid dynamics (CFD) simulations. These two fields were combined within a research project in order to design a new system for continuously monitor the efficiency of hydraulic turbines. With the use of CFD, the first part of the paper shows that the precision of usual index methods, like Winter-Kennedy (WK), is limited in semi-spiral casings as a result of sensitivity to inlet conditions and guide vane opening. The second part of the paper addresses the previously identified weaknesses by using a much larger pressure difference and calibrating it against the guide vane position. Experimental results confirm the validity of the proposed method.

INTRODUCTION

For a utility such as Hydro-Québec, the operation of low head plants, which are normally run-of-river, is somehow problematic since the optimal operating point can vary considerably depending on the flow conditions. Among the various factors involved, the main one is naturally head variation but there is also some effects related to trash rack clogging, operation of adjacent groups, air injection from the shaft, downstream levels fluctuations and degradation of the hydraulic profile. One obvious possibility to obtain all the required information is to do extensive measurements (absolute discharge) but it is often not feasible because of the time and money constraints. A more realistic approach to obtain the global picture is to continuously monitor the flow. In this context, a research project on efficiency monitoring was started in 2002. The project's objective was to maximize energy output and operational maintenance by improving the knowledge of the flow going trough the unit at all time. To be successful, the system had to be more accurate than what is currently available and to be deployable at low cost.

PART I: Sensitivity of Winter-Kennedy index to flow conditions

Because of their simplicity and low cost, pressure indices are often used during efficiency measurements to confirm the shape of the efficiency curve. Besides the well-known Winter-Kennedy index which uses the dynamic pressure in a spiral casing section, every hydraulic phenomenon that evolves as the square root of the flow rate (such as losses) can also be used as an index. Often the combined losses from the trash rack and intake channel can be successfully used to obtain a good index. However, since the rack clogging can vary quickly, this index is only valid for a limited period of time. As shown in Eq. 1, the principle of these relative methods is always to link the flow rate (Q) to the square root of the index (□P) via a constant (K). The exponent (b) is usually set at 0.5 but the IEC 60041 code [1] allows for some variation between 0.48 and 0.52 to obtain a better fit. However this is purely an empirical correction since there is no scientific reason that justifies it.

Eq. 1 $$Q = K * \Delta P^b$$

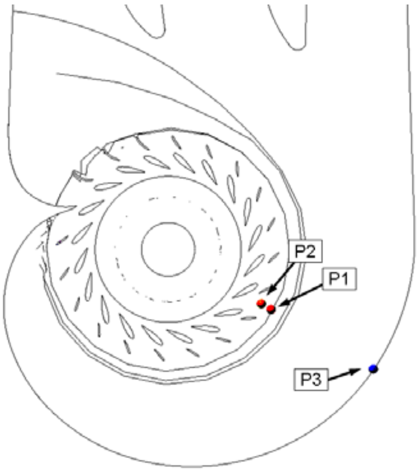


Figure 1: Geometry and position of the WK probes

Under good conditions, the relative index will have an accuracy of about 1% while under the worst conditions, usually met in low-head plants, it may not work at all as in Kerkan [2]. The reasons why WK indices are useful in some plants and useless in others has never been explained before. One of the basic assumptions required for using those methods is that the flow in the region of interest remains similar under every condition. This came from the Bernouilli assumption that is only valid along a stream line. With the help of CFD simulation, this homology condition was investigated regarding the influence of guide vane opening and inlet conditions.

The LG-1 power plant located in northern Québec was chosen for this investigation. One of the main reasons for this was the availability of tests results at various heads. Each of the plant's 12 propeller turbines can generate 110 MW under a normal head of 27.5 m. The semi-spiral casing has three inlet channels covering a width of 22 m and a height of 18 m. It has 24 guide vanes. The position of the WK probes is shown in Fig. 1.

NUMERICAL SIMULATION SETUP

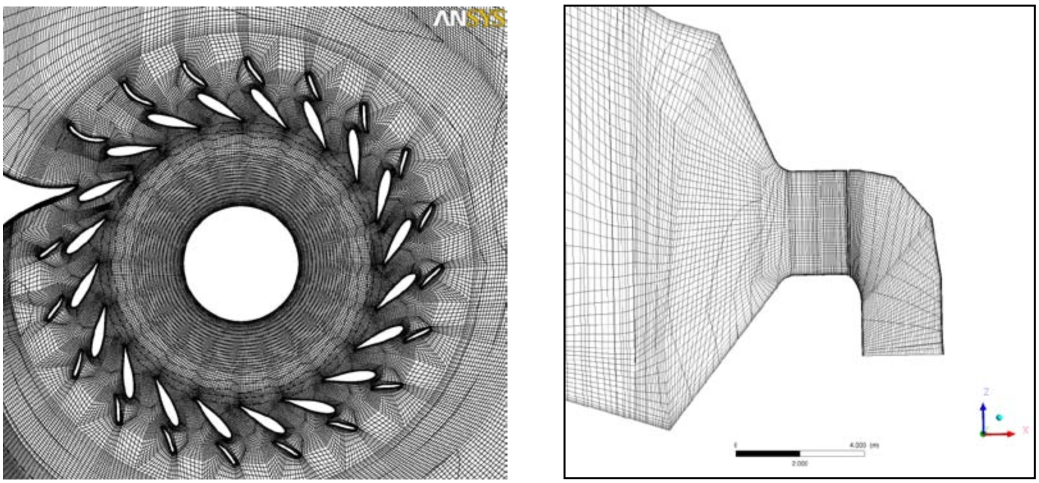
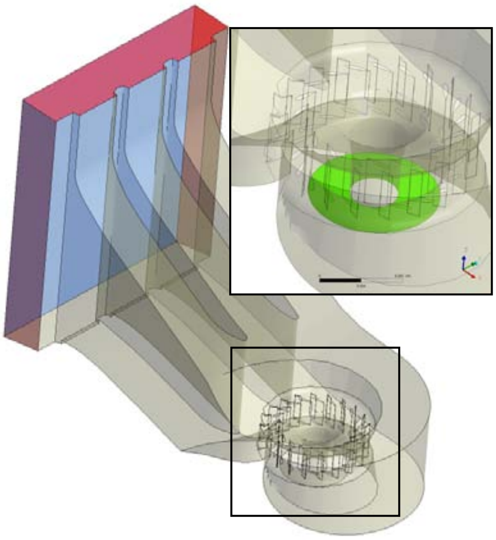


Figure 2: Details of the spiral casing mesh

The geometry of the semi-spiral casing was incorporated into CAD software using drawings. The inlet's upper surface was set at the normal operating level of the reservoir and the sides were modeled in the middle of the pier separating the units. A structured mesh was then created with IcemCFD for seven different guide vane openings covering a wide operating range. The mesh included 6.7 M hexahedral elements and was refined near the walls and in the distributor area to account for the velocity gradient. A close up view of the mesh is presented in Fig. 2. Part of the meridian channel up to the runner position was also represented to move the outlet boundary condition away from the region of interest. The turbine itself was not included in the simulation.

CFX-11 was used to solve the steady flow. The measured flow rate was imposed at the inlet (in blue in Fig. 3) along with a 5% turbulence intensity. An average static pressure was used at the outlet (in green). When studying the influence of the guide vane position, the top and sides of the inlet area (in red) were considered as symmetry planes so no flow was allowed to cross them. The standard K-epsilon model with scalable wall functions was used to represent the flow turbulence. The walls were modeled as smooth. As a tradeoff between robustness and accuracy, the spatial resolution scheme was set to be 75% second order accurate by using a blending function with the upwind scheme. The solution was considered converged and the calculation stopped when the maximal residuals in the solution were below 1E-4 and the global engineering quantity such as losses and pressure differences were stable.



SENSITIVITY OF WK TO GUIDE VANE POSITION

Fig. 3 Boundary conditions for CFD

First, the flow distribution between the three inlet channels was used to check if the overall behaviour of the spiral casing was correctly predicted. As can be seen in Table 1, when compared with measurements previously done with current meters [3], the numerical results showed the proper distribution between channels.

Table 1: Flow distribution at the inlet channels

	Flow [m3/s]	% left channel	% center	% right channel
CFD	443.2	36.3	34.3	29.4
Exp [3]	447.1	36.3	35.1	28.6

Next, the guide vane angular position was modified to determine its effects on the spiral casing flow and on the various indices. The impact of opening the guide vane is to align them with the flow thus lowering their losses. These losses, which can be assimilated to hydraulic resistance, tend to level the flow distribution between the different sectors. As can be seen in the left part of Fig. 4 which presents the normalized massflow through each sector, there is more flow passing trough the upstream sectors as the opening of the distributor increases. At full opening, the 6th sector sees about 103% of the average flow. The fact that the flow is changing is a first sign that any flow measuring system based on the dynamic pressure monitoring should be used cautiously.

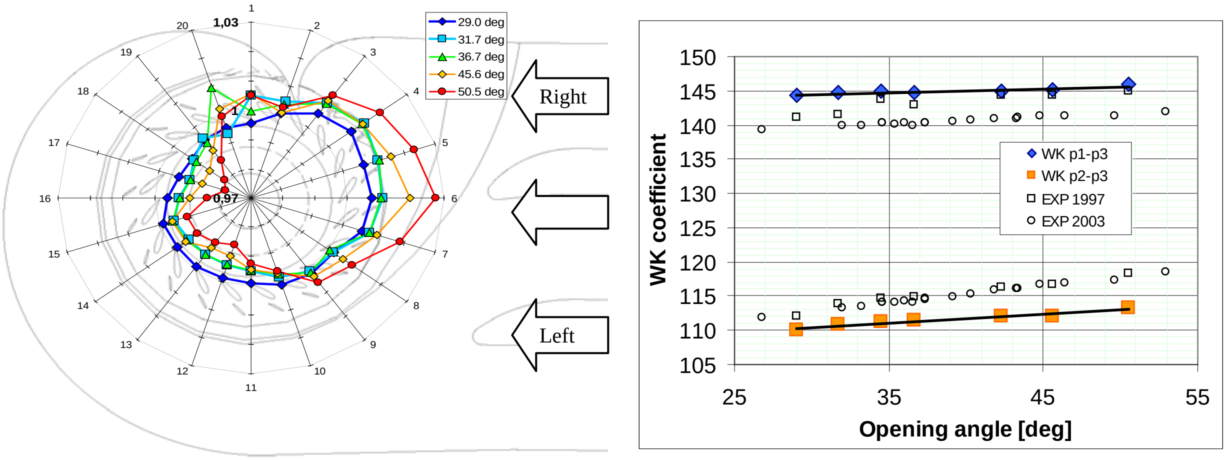


Figure 4: Flow distribution and WK coefficient evolution with opening

The right part of Fig. 4 presents the calculated and measured WK index coefficient based on the pressure difference and the measured flow rate. If the WK constant was independent of the opening, it would be an horizontal line on the plot. The slope clearly shows that the modifications in the flow distribution between the different sectors also impact the WK readings. Given the fact that no geometrical verification of the probe position and condition was done, they compare relatively well with the value determined experimentally with previous current meter measurements. Discrepancies between numerical and experimental coefficients were also obtained by Muntean [4]. Since its inner probe is located at a greater radius, the WK_{P1-P3} is less sensitive to the guide vane position than the WK_{P2-P3}. However the latter is usually the one that is used because it sees a larger pressure difference which usually translates into more signal stability [2]. Assuming a constant value corresponding for the WK coefficient would introduce an error on the estimated flowrate that could reach ±1.5% at full load. This sensitivity compares wells with the 1.2% obtained after six months of following the WK index in one of the first attempts of online efficiency monitoring (see Streat [5]).

SENSITIVITY OF WK TO ADJACENT UNIT OPERATION

To simulate the operation of adjacent units, the boundary conditions imposed on the inlet were modified while maintaining all other factors constant. For these tests, the inlet's sides could be included in the inlet or left as a symmetry plane. The basic assumption was that when the adjacent unit was in operation, the flow could not come from this side, therefor a symmetry plane was a reasonable approximation. In all situations, the upper surface remained a symmetry plane. This allowed for four different inlet boundary conditions to be tested. The summary of those tests is presented in Fig. 5.

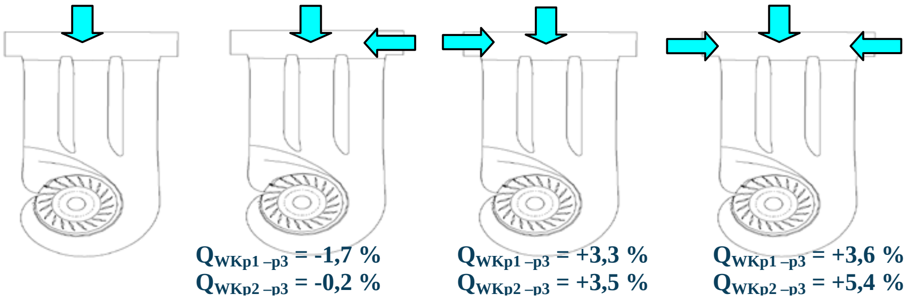


Figure 5: impact of inflow conditions for WK index

Although the inlet was probably too short to properly represent the incoming flow from the reservoir, this sensitivity test still gives a good indication of the validity of the chosen index. The two WKs are shown to have an average variation of 3% when modifying the inlet conditions. This is understandable since the measured pressure difference is only a few KPa (9.3K Pa for WK_{P2-P3} and 15.8 KPa for WK_{P1-P3}), so it is easily affected when upstream condition changes.

So here is the paradigm of the WK relative index method. It does not seem is not possible to have an index within the spiral casing that is at the same time independent of the opening and stable regarding adjacent unit operation. This is because the flow homology condition required is not fully observed. To be independent of the moving parts, the pressure probes must be positioned far enough of the guide vane. However to be stable regarding adjacent unit operation, they must also measure a significant pressure difference. This duality limits the accuracy of the WK system for continuous flow monitoring.

PART II: New method for continuous efficiency measurement

NUMERICAL RESULTS

To improve relative measurement accuracy, a correction factor can be implemented for the guide vane position. As shown in Eq. 2, this means that the index constant K would no longer be universal but would vary with the opening. Since the guide vane position is usually known, it is important to understand that this system will still have only one degree of freedom i.e. one flow rate for a given pressure/opening combination. What is more interesting is the fact that, since there is already some correction for the moving parts, there is no reason to be away from the guide vane anymore. This allows for a large increase in the measured pressure difference, thus lowering the sensitivity to inflow conditions.

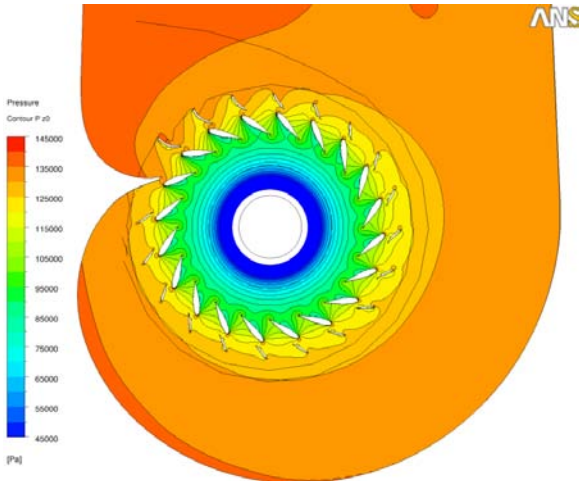


Figure 6: Pressure distribution in middle plane

Fig. 6 shows the static pressure distribution in the middle plane of the spiral casing. The WK indices are placed in the orange-to-yellow region. As one can see, the measured pressure difference would be much higher if the downstream probe was placed closer to the unit axis. As shown in Fig. 7, two different locations downstream of the guide vane were monitored on the meridian channel, one on the upper cover (P_{sup}) and one on the lower cover (P_{inf}). Coupling them with an upstream WK probe (WK_{P1} in this case) allowed three different indices to be monitored.

Eq. 2 $$Q = K(op) * \sqrt{\Delta P}$$

As shown in Fig 8, the coefficient calibration curves obtained from the CFD simulation were smooth and very good correlations could easily obtained with low order polynomial functions. The exact positioning of the probes is not important since the calibration is done afterwards. It can also be seen that the coefficient increases with the opening. As expected, the WK coefficients are relatively constant given the plot scale. Since the sensitivity of the index is related to the magnitude of the measured pressure difference, a good index would always have a coefficient that is as low as possible. In other words, to improve on the WK, the coefficient m vhen u

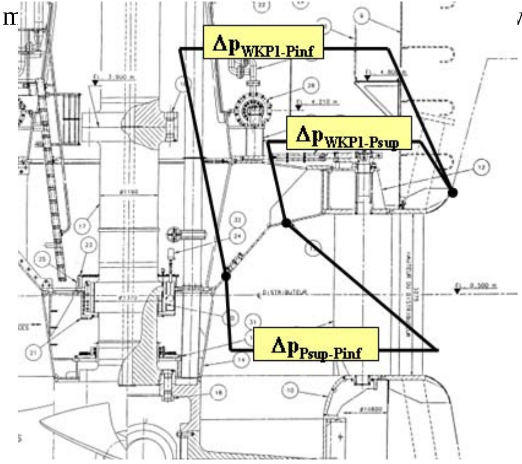


Figure 7: Pressure probe position for new index

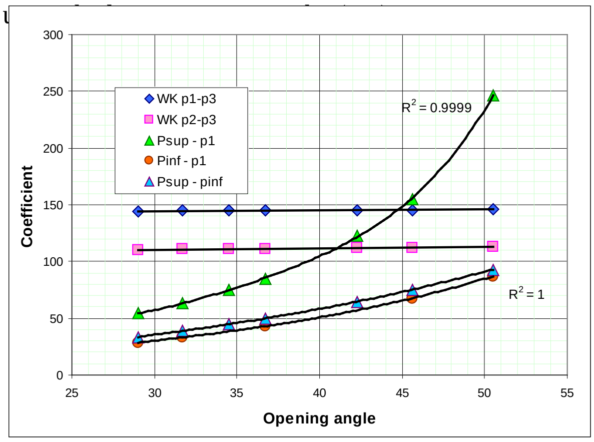


Figure 8: New calibrated index coefficient evolution

The $P_{WKp1}P_{inf}$ index coefficient was estimated with a third order polynomial fit (Eq. 3) based on five of the previously calculated opening angles. To see how the method performs, the flow was then predicted for the remaining two openings (34.5 and 42.3 degrees). In a third test simulating a head change, the flow was increased by 10% at the nominal opening (36.7deg). As it can be seen in Table 3, by combining the polynomial function and pressure difference, the method was able to capture the flow variation quite well for the three points that were not included in the calibration process.

Eq. 3 $$K = 0.0014449x^3 - 0.10625x^2 + 4.1499X - 37.681$$

opening	29 deg	31.7 deg	36.7 deg	45.6 deg	50.5 deg	34.5 deg	42.3 deg	36.7 deg Q+10%
Flow [m3/s]	368	403.4	443.2	485.7	506.7	425.3	471.4	487.5
□$R_{WKp1-Pinf}$ [KPa]	166.21	148.26	106.53	51.58	33.91	122.54	67.83	128.58
K Coefficient	28.55	33.13	42.94	67.63	87.01	38.36	57.10	42.94
Predicted flow [m3/s]	367.97 (-0.01%)	403.38 (-0.01%)	443.16 (-0.01%)	485.66 (-0.01%)	506.66 (-0.01%)	242.78 (-0.16%)	471.54 (-0.23%)	486.91 (-0.12%)

Table 2: Predicted flow rate for various openings and conditions

To verify the sensitivity of the calibrated index to inflow conditions, the predicted flow rate was analysed in a similar way as for the WK. As shown in Fig. 9, the results were less affected than the WK probes, thanks to the large increase in pressure difference and the filtering effect of the guide vane.

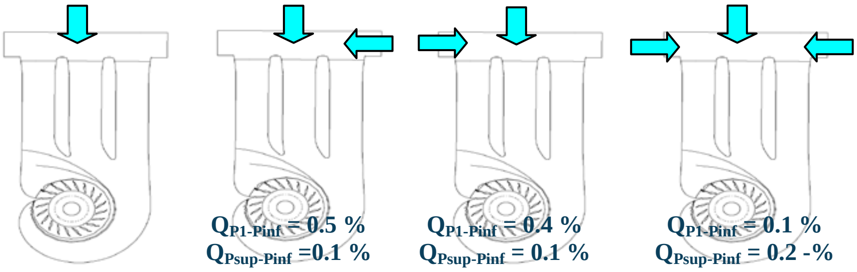


Figure 9: Impact of inflow conditions for the new index

EXPERIMENTAL RESULTS

The numerical results were encouraging enough but the new method still had to pass the field test. In order to evaluate the sensitivity of the new index measurement as well as the classical Winter Kennedy index, the system performance was monitored on the Unit no. 5 over a six month period in 2008-2009.

Fig. 10 shows the measurement error over a period of two days when either of the adjacent units (no. 4 and no. 6) was started or stopped. Flow measurement was done by measuring the pressure difference between one of the pressure taps of the cover (P_{inf}) and one of the Winter Kennedy taps (WKP3 in this case). It shows that starting or stopping unit no 4 or 6 clearly affects the flow measurement given by the classical WK. The measurement error reaches 1% from the condition of the Unit no. 6 being stopped and Unit no. 4 running compared to the reverse. It is evident that the velocity profile in the WK taps section is immediately affected when one unit is stopped. In addition, the measurement error on the WK seems to evolve slowly while the adjacent units remain at rest. This has yet to be explained but could be related to the time constant of the upstream reservoir. As expected from the numerical simulations, the new index method is influenced by the operation of adjacent units to a far lesser extent.

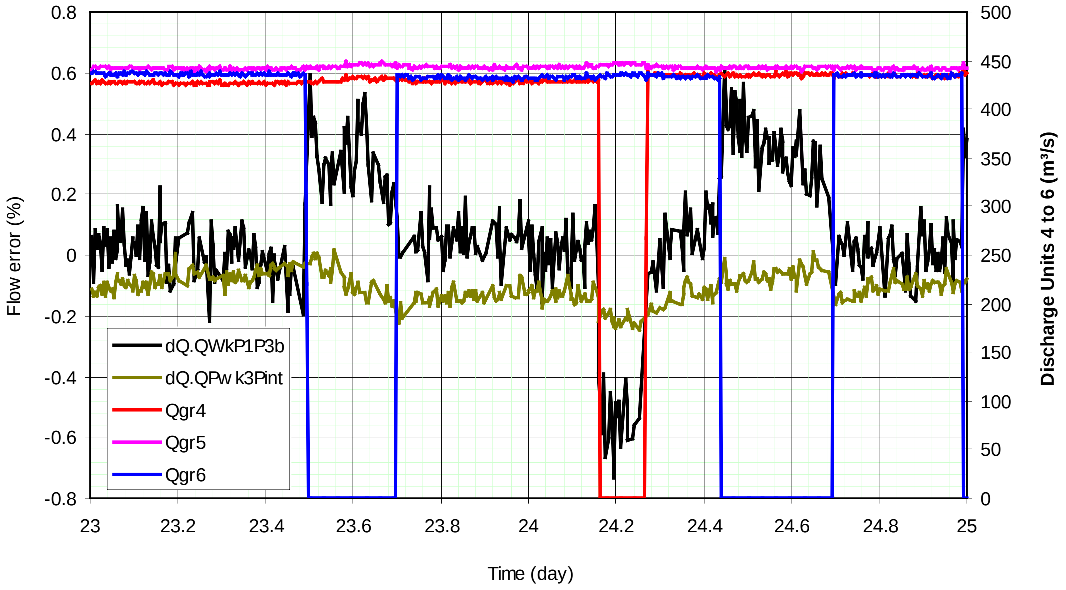


Figure 10: Flow measurement error of the new index method and discharge of adjacent units

Table 3 gives additional insight on the performance of the system by showing the standard deviation of the flow measurement over a period of 50 days. The operation during this period consisted mainly of a combination of optimal and peak loads in a context of high demand due to electric heating in the winter. The calibration of the various indices was done by setting the average error to zero for each method. The samples were taken as 5 minutes averages and were filtered to represent only steady operation.

Two methods were used to obtain the flow rate from the WK index. The classical WK method used a fix coefficient and allowed for variation of the exponent (QWkP1P3b and QWkP2P3b) as in Eq. 1, while the alternative method (QWkP1P3 and QWkP2P3) used a variable coefficient and 0.5 for the exponent as suggested in this paper (Eq. 2). As often experimented, because of its higher pressure difference, the WK_{P2-P3} has the best performance of the two WK indices. However, it is interesting to note that applying a correction for the guide vane position can improve the performance of this index further. Also, the effect of the operation of Unit no. 4 is shown to be greater than that of Unit no. 6. This can be easily explained because Unit no. 4 is next to the left channel where the WK probes are located.

With regards to the performance of the new index, one of the new index measurements (Pwk1 - Psup) shows an error of the same magnitude as the WK method. This is the measurement with the lowest pressure difference among the new index methods; in fact, it was about the order of magnitude of the WK pressure difference. Globally, when compared to the usual WK method (QWkP2P3b), the most representative index of the new method (QPwk3Pinf) cuts the error by half. This performance could probably be improved even more if, instead of using the WkP3, a pressure more representative of the upstream condition in the spiral casing could be used.

Table 3: Standard deviation of flow error for various index methods

Index method	All data	Unit 4 stopped	Unit 6 stopped	Units 4 and 6 stopped	Units 4 and 6 running	
QWkP1P3	0.1902	0.4886	0.2517	0.3218	0.1656	WK
QWkP1P3b	0.1939	0.4834	0.2584	0.3021	0.1692	
QWkP2P3	0.1141	0.2088	0.1568	0.1372	0.1014	
QWkP2P3b	**0.1523**	0.1882	0.2102	0.1339	0.1389	
QPwk1Pinf	0.0810	0.1165	0.0756	0.1204	0.0805	New index method
QPwk1Psup	0.1420	0.1217	0.1455	0.0709	0.1430	
QPinfPsup	0.0752	0.1243	0.0813	0.1375	0.0713	
QPwk3Pinf	**0.0658**	0.1343	0.0698	0.1454	0.0616	
QPwk3Psup	0.0648	0.1762	0.0654	0.1408	0.0600	
Occurrence (5 min)	10223	248	1767	128	8080	

CONCLUSION

While many papers mention the possibility of monitoring flow rate with the WK probes, many also reported experiences that were not so conclusive, especially in low-head plants. Frequently, different coefficients were found at various heads and exponents had to be modified accordingly to obtain a good fit. On the whole, those systems had limited range and were not very useful for predicting the flow under all conditions. By combining CFD and experimental expertises, a project was started to better understand what was going on with index testing and to develop a new system for monitoring the flow rate that could be installed in most plants. This paper demonstrated by numerical and experimental means that the sensitivity of the WK index measurement technique is limited because the flow homology condition is not always observed.

By placing a pressure probe on the cover of the meridian channel behind the guide vane and calibrating the obtained index with the angular position of the distributor, a much better indication of the flow passing trough the turbine can be obtained. Since the calibration is mostly geometric, the suggested method theoretically allows for comparison between similar units. Moreover, as the calibration curve is valid at any head, it could save the time and money to measure at various head. The system works well for propeller units. Early results (not presented in this paper) show that it can also be used with similar success in Francis turbine. For Kaplan turbines, the system would need to be adapted to include the blade pitch because of the change in meridian channel flow distribution. This would turn the problem into determination of a calibration surface instead of a calibration curve. Unfortunately, this also means that such a method could not be used if the runner is replaced because a new calibration curve would then be necessary.

The calibrated index method is one more tool available to field engineers to validate their results and a way to add some value to absolute efficiency testing since it can provide continuous information on unit performance after the measurement is done. This implementation could also potentially be used for maintenance purposes, in order to decide when to clean the trash rack, for instance. It is also important to mention that properly placed pressure probes behind the guide vane are often already available in more recent powerhouses. These were used during unit startup in order to monitor the rotor/stator interaction but were often abandoned afterwards.

Many of the results presented in this paper were based on CFD simulations. These simulations are very useful for flow investigation and usually give the right trend and proper order of magnitude of a given phenomena. However, they also have many internal limits such as turbulence modeling, wall roughness representation, numerical dissipation and mesh sensitivity. Judgment must be used when dealing with theses aspects. The fact that the calculated calibration curve and WK constants did not match the measurements is to be borne in mind since the entire method is based on the link between the index coefficient and the guide vane opening.

For the time being, the challenge will be to further investigate the accuracy and limits of the proposed method. The best way to obtain the calibration, either numerically, experimentally or with a combination of both, is also a subject of interest. Finally, and this may be the greatest challenge, the system will have to leave the research field to integrate operational practices in order to generate some added value.

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