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Experience with Winter-Kennedy coefficients on hydraulic identical units

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1. ABSTRACT

Depending on the arrangement of a Hydroelectric Power Plant, the measurement of the absolute efficiency according to the “IEC 60041 Third edition 1991-11” could be an expensive and challenging task. Predominantly these verification measurements are only performed at one unit of a power plant. In addition to one of the primary methods the so called “Winter-Kennedy” measurement gives an indication of the unit flow. Derived from the differential pressure at a certain location, characteristic unit coefficients can be determined. These coefficients can be used for efficiency tests on the other units under the assumption that the hydraulic design of the machines and the arrangement of the Winter-Kennedy measuring points are identically.

In practice the stability of these coefficients are not as they thought to be. This paper describes practical experiences and consequentially the sensitivity of the Winter-Kennedy measurement.

The efficiency tests on which this paper is established were performed at two Francis turbines. Primary efficiency method was the measurement with pressure-time method. Due to the complex test sequence, the measurement was scheduled at one unit only. The acceptance test for the second unit of the power plant was performed with the calibrated Winter-Kennedy coefficients, but in spite of identical units and same measuring positions the shape of the efficiency curve could not be reproduced. Hence the pressure-time method had to be performed on the second unit, too. Consequential new Winter-Kennedy coefficients results for the second unit even though the same measuring conditions occur on identical hydraulic design of the units.

2. INTRODUCTION

To verify the turbine efficiency, an acceptance test at a Francis turbine with two identical units was performed with the pressure-time method.

. In parallel to the absolute efficiency testing the Winter-Kennedy differential pressure was recorded. After finalization of the first unit the Winter-Kennedy exponent and the constant was determined to use these values for performing a Winter-Kennedy test at the second unit. This procedure should save time and effort for the measurement of the second unit.

After preliminary evaluation of the test results from both units non negligible differences in the efficiency values occur. There were no arguments against a failed measurement except of that for the same discharge different differential pressures occur for the two identical units. This adoption realized a repetition of the test at the second unit with the pressure–time method. Consequently a comparison of the two pressure-time measurements showed only negligible differences in the efficiency values.

3. METHOD

3.1. Principles of Pressure-time method

The pressure - time - method was presented in the early twenties by Norman R.Gibson and is based upon Newton's second law of motion (Gibson N. R., 1923) (Gibson N. R., 1959). The deceleration of the mass of water in the closed conduit is forced by a closure of gates. Gates means any closing device such as guide vanes or main inlet valves. There are mainly two basic procedures of the Gibson method: The single and the differential method. It is common to use the differential method using two measuring sections in the conduit. This method minimizes uncertainties due to the determination of boundary conditions. All further explanations are given for the differential method.

The second law of motion is expressed by $F=m*dv/dt$ where F is a force acting on the mass of water m. Expression dv/dt is the rate of change of the velocity (deceleration in this case) of that mass of water. The change of velocity dv/dt in a conduit of constant cross section A of a mass of fluid $\rho*L*A$ between the two measuring sections leads to a differential pressure h between the upstream and downstream cross section.

$$\rho \times L \times A \times \frac{dv}{dt} = -A \times h$$

Equation 1

If t is the time during which the velocity changes one get:

$$A\int_0^t dv = -\frac{A}{\rho L}\int_0^t (h+\xi)dt$$

Equation 2

The integration of the function $(h+\xi)$ leads to the change of the initial velocity before closure and the velocity after the closure which should be zero. If there is a remaining flow the leakage flow *q* has to be measured separately. Thus the discharge *Q* for the stationary operation before gate closing considering the leakage flow *q* through the gate is then:

$$Q = \frac{A}{\rho L}\int_0^t (h + \xi) dt + q$$

Equation 3

The measurement of the initial velocity (e.g. the discharge *Q*) requires the determination of the distance *L* between the measuring sections and the cross sectional area *A* of the measuring sections. The impulse due to the change of velocity can be obtained by producing a pressure – time – diagram. (IEC60041, 1991-11)

3.2.Principles of Winter-Kennedy method

In 1933, Ireal A. Winter and M. Kennedy published a paper, "An Improved Type of Flow Meter for Hydraulic Turbines," describing what today is known as the Winter-Kennedy method to measure relative flow rates in hydraulic turbines. In principle the method is based on the correlation between the flow rate passing through the turbine and the difference in pressure between the concave and convex surfaces in the curved portion of a spiral or semi-spiral case. At least one pair of piezometers is necessary which are located on the inside and outside of the spiral case. (Winter & Kennedy, 1933)

The differential pressure *h* between the two taps is related to the discharge *Q* through the following relationship:

$$Q = a \times h^n$$

Equation 4

The coefficient *a* and the exponent *n* are two constants. According to IEC 60041 *n* is theoretically 0.5 but in practice the exponent may change between 0.48 and 0.52. These two constants will be in focus within this paper. A detailed description of the method is shown in the international standard IEC 60041. (IEC60041, 1991-11)

3.3.Arrangement of Winter-Kennedy differential pressure taps

For different type of machines different application of Winter-Kennedy differential pressure taps are necessary. Figure 1 shows a short overview for Francis/Kaplan turbines with full spiral case, for Kaplan turbines with semi spiral case and bulb turbines. The different arrangements are according IEC60041.

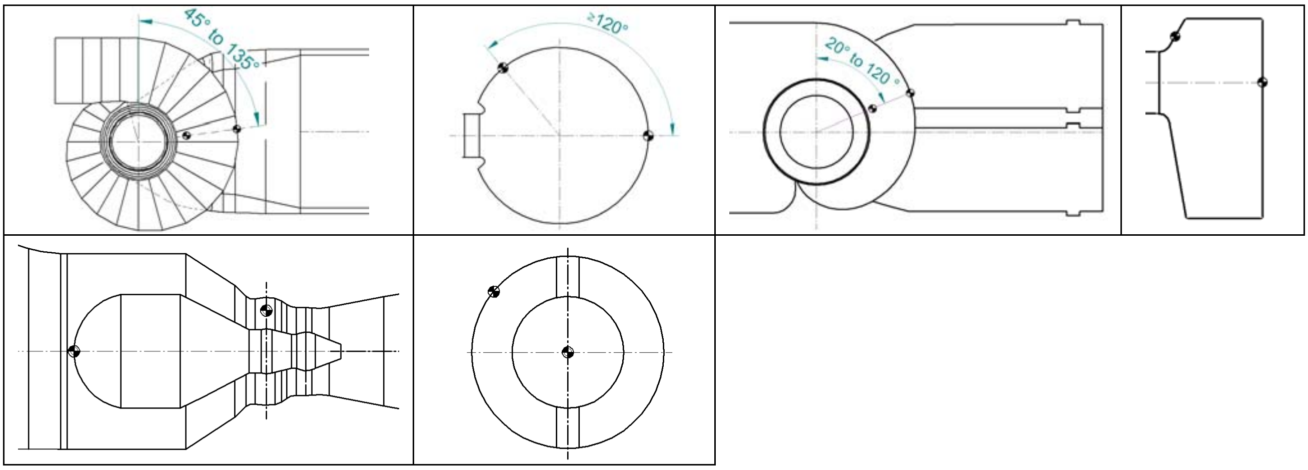

Figure 1: Arrangement of Winter-Kennedy differential pressure taps

3.4. Description of power plant arrangement and measuring points

Two Francis turbines with equal water ways are installed at the power plant where the measurement takes place. The technical specifications of each machine group are:

Tab. 1 Technical Specification

Name	Value
Net head [m]	311
Discharge [m³/s]	17.6
Power [MW]	49.5
Speed [1/min]	600

Figure 2 shows the water ways upstream and downstream of the turbine. The upstream water way consists of one reservoir, the headrace tunnel, the surge tank, the penstock, the bifurcation and penstocks to each turbine. The tail water channel is only separated through a short outlet from the turbine.

In front of the bifurcation there is an assembly to a pipeline which is connected to a separate reservoir (see Figure 3). The flow from the pipeline to the penstock is automatically regulated by a valve; the valve is located directly in front of the bifurcation. During the whole measurement campaign the valve was closed.

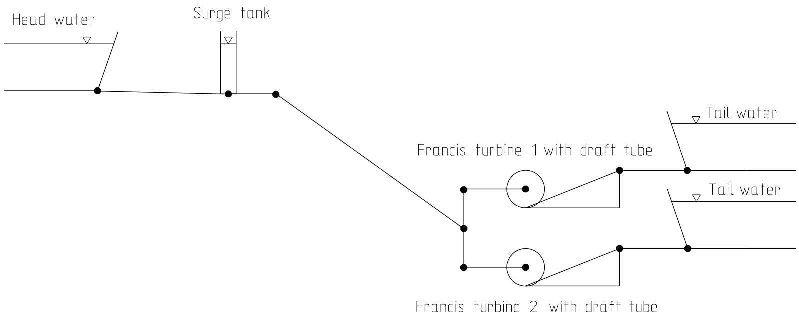

Figure 2 Schematic arrangement of water ways

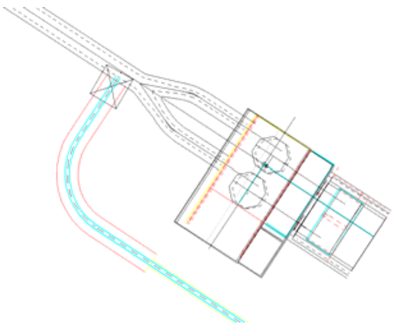

Figure 3 Bifurcation with a separate pipeline

For verification of the turbine efficiency the pressure-time method was conducted. Therefore two measuring section with a distance of 50 m were prepared at an accessible part of the penstock. At each section four measuring points were arranged. Every measuring point had its own piping to the middle of the sections. For higher reliability each of the measuring pairs will be recorded separately. Figure 4 and Figure 5 show the arrangement of the measuring points in the two sections for the pressure-time method.

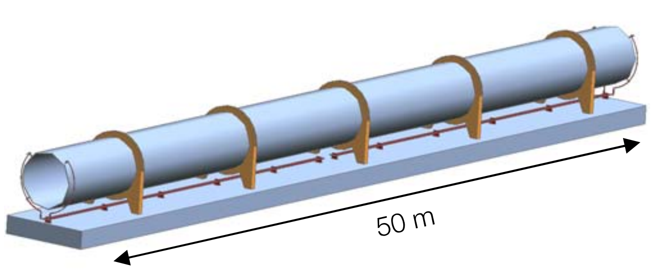

Figure 4 CAD model of the pressure-time measurement arrangement

Figure 5 Pressure-time measuring points

4. Performing of the measurement

4.1. Procedure

The measurement by pressure-time method was scheduled at one unit only. The same behavior was expected for the second one because of identical units and the same arrangement of measuring positions. In agreement with the customer the derived Winter-Kennedy coefficients should be used for verification of the second unit. Following procedure was arranged for the test:

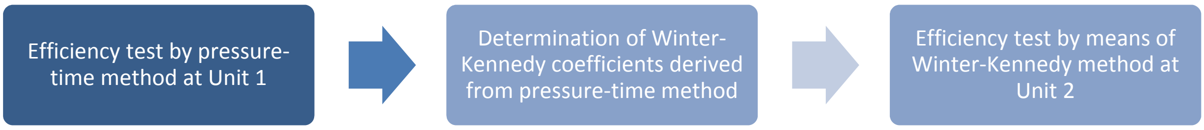

Figure 6 Primary procedure of the test sequence

The acceptance test for the second unit of the power plant was performed with the calibrated Winter-Kennedy coefficients, but the shape of the efficiency curve could not be reproduced. Hence the pressure-time method had to be performed on the second unit, too. The results will be shown in the following chapters.

4.2. Results of pressure-time method

Figure 7 shows a comparison of the measured efficiency curves by means of the pressure-time method of both identical units. Both curves fit very well without any higher discrepancy. The shape of the curve is almost the same compared with the other unit. Consequently no identification for any discrepancy in the performance of the two units can be detected. In spite of everything a verification of Unit 2 under consideration of the Winter-Kennedy coefficients of Unit 1 was not possible.

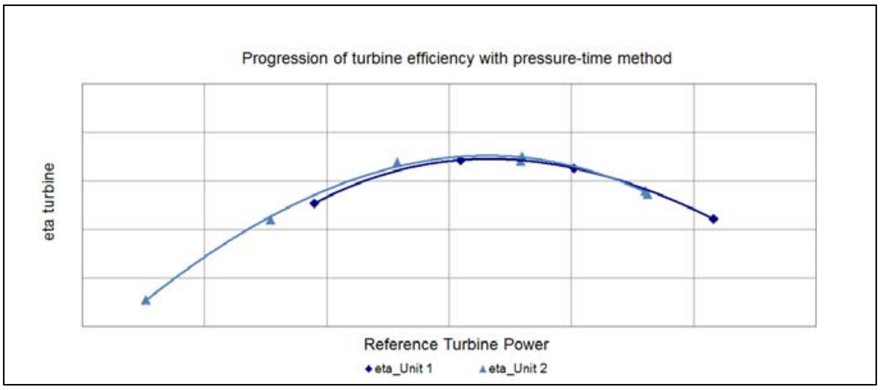

Figure 7 Comparison of turbine efficiency measured by means of pressure-time method at both units

4.3. Calibration of Winter-Kennedy measurement with results of pressure-time method

Derived from the primary method the Winter-Kennedy coefficient and exponent could be determined. The calculation of the Winter-Kennedy constant and coefficient was made according "*Technische Richtlinien für die Spiralendruckmessung und andere Differenzdruck-Meßverfahren in Wasserkraftanlagen" - 2.Ausgabe 1974* (Elektrizitätswerke, 1974). The direct method was applied and will be explained with the following formula:

Depending on the number of measuring points different formulas are given.
Even number of measuring points: *m=2k*

$$\log Q1 = \frac{2}{m} \times \sum_{i=1}^{k} \log Q_i \qquad \log h1 = \frac{2}{m} \times \sum_{i=1}^{k} \log h_i$$

$$\log Q2 = \frac{2}{m} \times \sum_{k+1}^{m} \log Q_i \qquad \log h2 = \frac{2}{m} \times \sum_{k+1}^{m} \log h_i$$

Equation 5 Evaluation of calibration equation - even number of measuring points

Uneven number of measuring points: *m=2k+1*

$$\log Q1 = \frac{2}{m} \times (\sum_{i=1}^{k} \log Q_i + \frac{1}{2} \log Q_{k+1}) \qquad \log h1 = \frac{2}{m} \times (\sum_{i=1}^{k} \log h_i + \frac{1}{2} \log h_{k+1})$$

$$\log Q2 = \frac{2}{m} \times (\frac{1}{2} \log Q_{k+1} + \sum_{k+2}^{m} \log Q_i) \qquad \log h2 = \frac{2}{m} \times (\frac{1}{2} \log h_{k+1} + \sum_{k+2}^{m} \log h_i)$$

Equation 6 Evaluation of calibration equation - uneven number of measuring points

The constants n and a yield:

$$n = \frac{\log Q2 - \log Q1}{\log h2 - \log h1}$$

$$\log a = \log Q1 - n * \log h1 =$$
$$= \log Q2 - n * \log h2$$

Equation 7 Formula for constants n and a according direct method

Following values were calculated for Unit1 and Unit2:

Tab. 2 Results of direct method - Unit1

Measured values		Position	Evaluation for calibration equation for h in bar					
Q [m^3/s]	h [bar]	h√Q	log Q	log h	log Q1 log Q2	log h1 log h2	log a	
18.115	0.2675	1.138498	1.258026	-0.572681	1.214901	-0.654212	1.548237	
17.882	0.2637	1.115159	1.252404	-0.578865				
15.490	0.1998	0.786519	1.190058	-0.699320				
15.688	0.2026	0.802395	1.195575	-0.693399				
13.867	0.1587	0.591037	1.141983	-0.799377				
14.071	0.1633	0.612497	1.148333	-0.787062	1.069736	-0.939116	1.548237	
12.124	0.1238	0.431055	1.083628	-0.907281				
12.041	0.1199	0.415915	1.080663	-0.921327				
8.515	0.0616	0.179654	0.930197	-1.210662				
			l1=log Q2-log Q1		-0.145165		**35.3375957**	**a**
			l2=log h2-log h1			-0.28490375	**0.50952301**	**n**

Tab. 3 Results of direct method - Unit2

Measured values		Position	Evaluation for calibration equation for h in bar					
Q [m^3/s]	h [bar]	h√Q	log Q	log h	log Q1 log Q2	log h1 log h2	log a	
17.554	0.2584	1.082583	1.244384	-0.587731	1.209326	-0.658697	1.538176	
17.561	0.2571	1.077389	1.244541	-0.589898				
15.554	0.1978	0.780114	1.191842	-0.703763				
15.564	0.2089	0.824239	1.192114	-0.680004				
13.746	0.1565	0.580228	1.138168	-0.805486				
12.038	0.1182	0.409942	1.080554	-0.927555	1.026403	-1.025097	1.538176	
10.411	0.0921	0.297113	1.017503	-1.035830				
10.372	0.0913	0.294187	1.015863	-1.039307				
8.626	0.0620	0.182138	0.935809	-1.207503				
			l1=log Q2-log Q1		-0.182923		**34,5283706**	**a**
			l2=log h2-log h1			-0.36640002	**0.49924337**	**n**

Therefore the calibration curve for Unit 1 and Units 2 yields:

$$Q = a \times \Delta p^{n} = 35.338 \times \Delta p^{0.5095} \; [\frac{m^3}{s}]$$

Equation 8 Winter-Kennedy coefficient and exponent for Unit 1

$$Q = a \times \Delta p^{n} = 34.528 \times \Delta p^{0.4992}\ [\frac{m^3}{s}]$$

Equation 9 Winter-Kennedy coefficient and exponent for Unit 2

4.4. Comparison of Winter-Kennedy coefficients

In addition to the measured and derived Winter-Kennedy coefficients from the pressure-time-method also the Winter-Kennedy coefficients from model test was taken into consideration for the resulting investigation. During the model test following correlation was determined for the prototype:

$$Q = a \times \Delta p^{n} = 33.7304 \times \Delta p^{0.5205}\ [\frac{m^3}{s}]$$

Equation 10 Winter-Kennedy coefficient and exponent from model test

Tab. 4 shows a summary of the different coefficients and exponents which were the initial point of this observation. The discrepancy of the coefficient *a* is very small and has no big influence on the shape of the curves. According to IEC code 60041 the exponent *n* should have a range between 0.48 and 0.52. The difference under consideration of the range is not negligible.

Tab. 4 Comparison of Winter-Kennedy coefficients and exponents

Winter-Kennedy	Derived from Gibson Test on Unit 1	Derived from Gibson Test on Unit 2	Model Test
Coefficient a	35.338	34.528	33.7304
Exponent n	0.5095	0.4992	0.5205

The discrepancy of the different exponents affects the efficiency trend as displayed in Figure 8. The first diagram includes the efficiency curves measured by means of Winter-Kennedy method on both Units. For both units the exponent and the coefficient derived from the pressure-time method at Unit 1 were used. In the lowest measured load point the efficiency curves fit quite well, but with higher loads the discrepancy increases up to 0.8%.

In comparison to that the shape of the curves evaluated by the coefficient and exponent which were determined during model test shows a similar behavior of the two units. In the lower parts the progression of the efficiency is consistent. With higher loads the difference increases up to 1.0%.

The calculated Index discharge over differential pressure displays a similar trend for both units without any significant discrepancy.

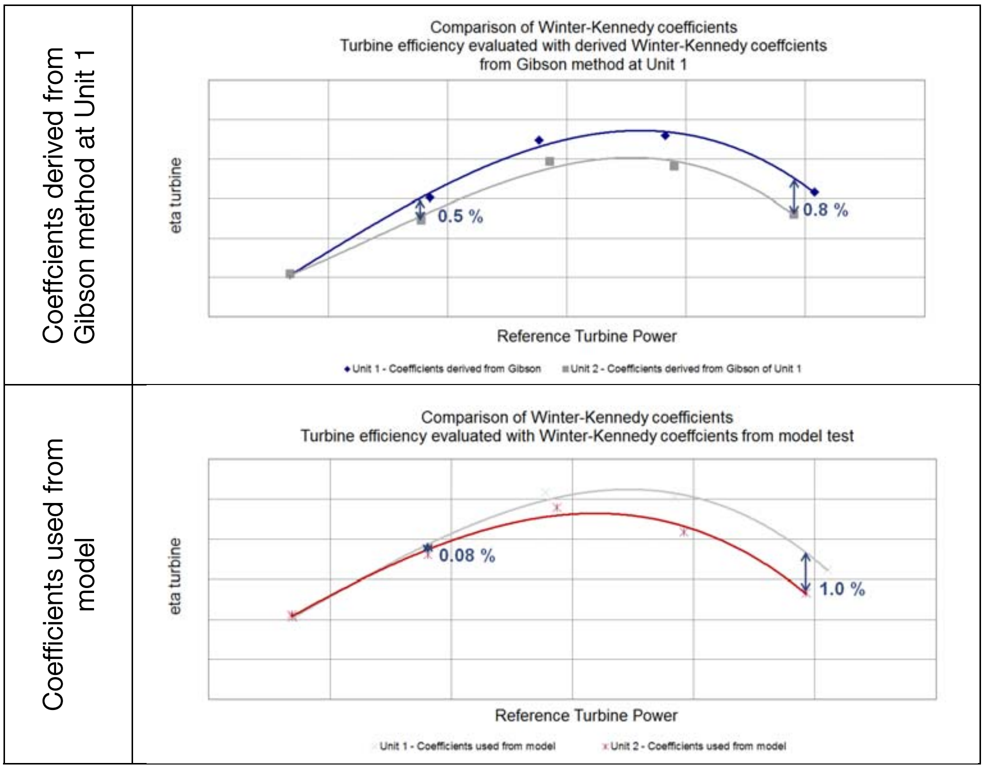

Figure 8 Comparison of Winter-Kennedy coefficients

4.5. Comparison of results

Due to the fact that the shape of the efficiency curve could not be reproduced the pressure-time method had to be performed on the second unit, too. Consequential new Winter-Kennedy coefficients results for the second unit.
Figure 9 shows the effect on the shape of the curves. The blue curves describe the efficiency trend based on Winter-Kennedy constants derived from the pressure-time method at its own unit. According to the initial intention the grey one is evaluated by the measured differential pressure at Unit 2 under consideration of the coefficient and exponent of Unit 1. Although the two units had an identical hydraulic design and the Winter-Kennedy measuring points were arranged at same positions a non-negligible drift occurs.
Under consideration of the new determined Winter-Kennedy constants the curves fit very well analogue to the results of the pressure-time method (see Figure 7).

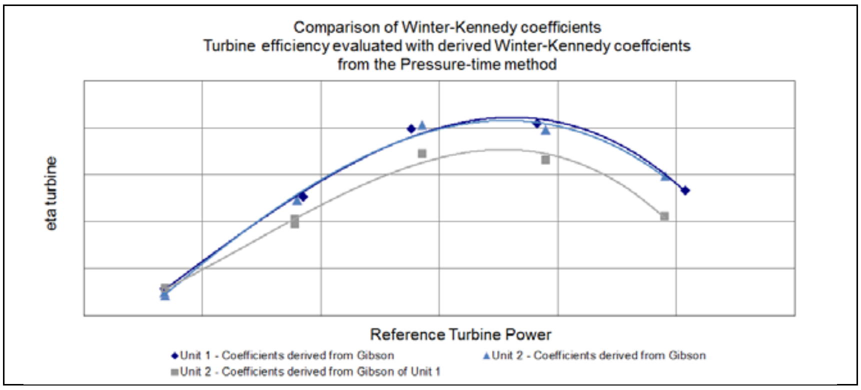

Figure 9 Turbine Efficiency evaluated with the derived Winter-Kennedy coefficients from pressure-time method

5. DISCUSSION

In general applications the acting of Winter-Kennedy differential pressure is very sensitive due to small physical values of the differential pressure. Special attention is required using the Winter-Kennedy differential pressure for comparisons of identical units, for comparison of rehabilitated units, for long term monitoring of efficiency or for permanent operation of the machine.

As discussed in this paper a discrepancy can occur at the differential pressure section between two hydraulic identical units. Although a CFD calculation showed a consistent flow distribution (see Figure 10) for the given arrangement the measurement evidenced different results.

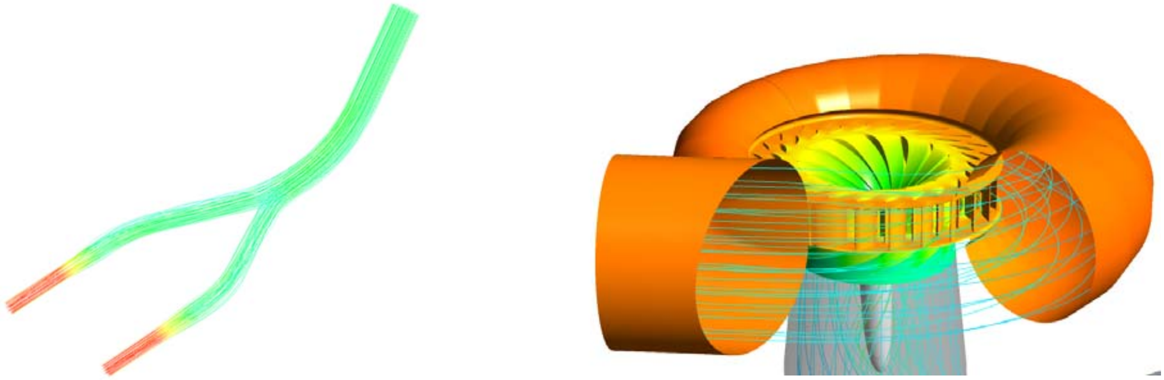

Figure 10 CFD Simulation at two hydraulic identical units

There are several reasons for discrepancies in the average Winter-Kennedy differential pressure which can lead to wrong results when this data is used for efficiency calculations or comparisons). It shall be clear for all parties in case of comparative tests (or other special testing) that following points can have influence on the Winter-Kennedy constant and exponent and hence on the results:

- Hydraulic boundary conditions
- Inflow conditions to the measurement plane (bifurcation, elbows, extraction or re-feeding of cooling water discharges near to the pressure tap, etc.)
- Design and the location of the taps and piping in the spiral case
- Wear at the pressure taps which can lead to surface irregularities and local disturbances of the flow
- Air pockets in the pressure piping especially for upward sloped piping

Figure 11: Example of pressure tap installations (good and bad realization)

In case of problems with the Winter-Kennedy differential pressure all of these points shall be checked. If such unfavorable conditions occur, a measurement/evaluation of these data does not make sense or is impossible and consequently another relative discharge measurement method or a primary method according IEC60041 should be considered.
It is not recommended to use the Winter-Kennedy measurement for comparative tests (e.g. measurement before and after rehabilitation or before and after uprating of a unit). Most probably the Winter-Kennedy constant and exponent will change that much that the comparison of the results is not valid anymore.

6. REFERENCES

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