Relative flow measurement with the pitot principle by means of sampling probe

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Abstract

One important aspect when commercially operating a hydro power station is the overall equipment efficiency of the plant and in detail the one of the Power Unit. As there are different runner types, also the final acceptance test method of the efficiency could differ. Independently of the measuring method, the biggest challenge is to define the flow that powers the unit. For new applications, special design provisions are considered in early stage to have the points at the right positions.

However, especially for old machines, often provisions for a relative flow measurement (e.g. Winter Kennedy) are not available. Sometimes the existing tapping/piping is damaged and cannot be reliably used anymore. For these cases, it would be useful to have the possibility to install a temporary and easy to apply relative flow measurement.

Further, during absolute efficiency testing (esp. for thermodynamic testing) it can happen that unfavourable measuring conditions occur at specific operation points, e.g., irregular temperature or velocity distribution or even unstable temperatures.

When the primary method shows excessive uncertainties or even fails completely in certain operating conditions, IEC60041 recommends using an Index test method as part of the field acceptance test. The idea behind that is to provide additional test data and / or the Index test method shall be calibrated by the primary method in the good operating range.

This paragraph was the motivation to consequently test the pitot principle in parallel to several thermodynamic efficiency tests. Practically the thermodynamic sampling probe, used blocked as a total head probe, and the pressure taps at reference section 1, used as a static head probe, were used for additional evaluations. Based on those values the differential pressure is derived to represent a relative flow value.

As the additional effort at site is almost negligible, data from several site test were evaluated and are presented in this paper.

This contribution describes the approach to those measurements. It describes the measurement points and the evaluations to gain a flow value and show the limits of application.

1. Introduction

Due to the incompressibility of the flow in a hydropower plant (the density of water is constant in the typical range of operation), the total pressure, p_{total}, (or stagnation pressure) is equal to the sum of the static pressure and the dynamic pressure at free machine flow. Since the water at the stagnation point is in rest, the dynamic portion is zero.

$$p_{static} + \frac{1}{2}\rho \cdot v^2 = p_{total} + \frac{1}{2}\rho \cdot (0)^2$$

Equation 1

$$v = \sqrt{\frac{2 \cdot (p_{total} - p_{static})}{\varrho}}$$

Equation 2: Velocity according Pitot principle

During several thermodynamic efficiency tests performed within the last years, additional measurements were taken to investigate this approach. Thermodynamic tests typically use sampling probes that extract a sampling flow from the main machine discharge, through an isolated measuring vessel, into the drainage. When the sampling flow is shut off, the sampling probe is effectively acting as a total head probe. Therefore, the total pressure at stagnation point can be measured when the sampling flow rate q is zero.

The static pressure in the spiral case inlet p_1 is always measured for efficiency testing since it is the reference section 1 for obtaining the net head.

The pressure difference between total head pressure $p_{1i'}$ $(q_i = 0)$ and static head pressure $p_{1'}$ can easily be calculated or better directly measured with a differential pressure transducer. If the fluid's density does not change, $\varrho = \text{const.}$, the fluids velocity is directly proportional to the square root of that pressure difference.

The aim of this approach is to generate a value that is proportional to the flow of the unit to be able to fulfil the standard when no other index test method is possible or unfavourable measurement conditions for the thermodynamic method occur. This approach is particularly interesting when using the thermodynamic method. Since the installation of sampling probes are typically required for the thermodynamic test, the additional effort is negligible.

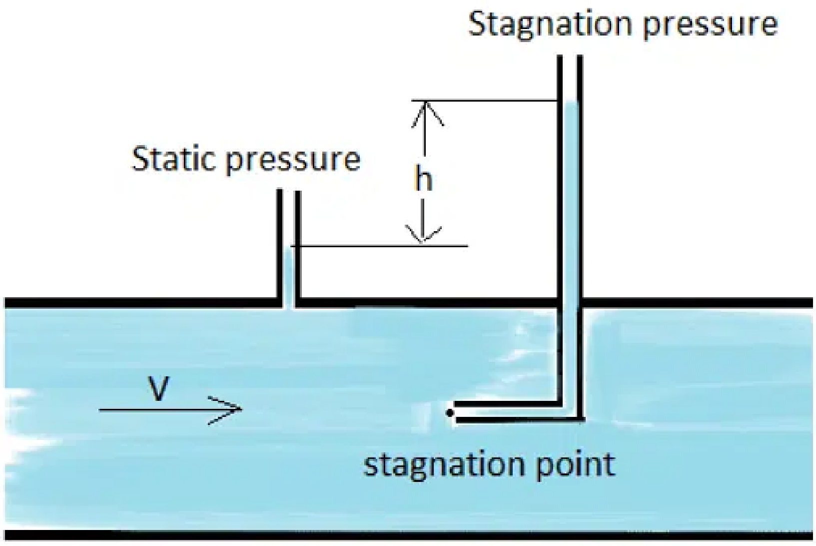

Figure 1: Sketch of the Pitot principle: $\boldsymbol{h}$ is directly proportional to the stagnation pressure and thus directly proportional to the square of the fluid's velocity $\boldsymbol{v}$.

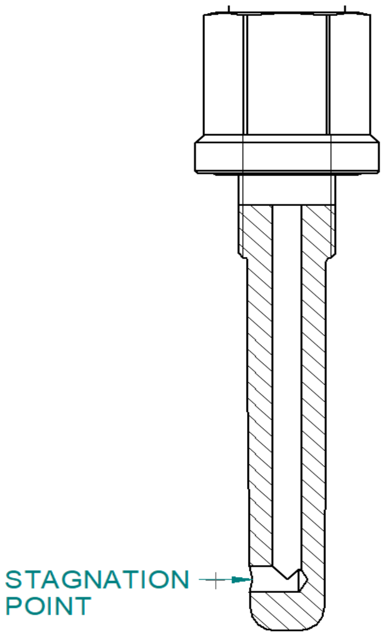

Figure 2 typical design of a sampling probe for thermodynamic test

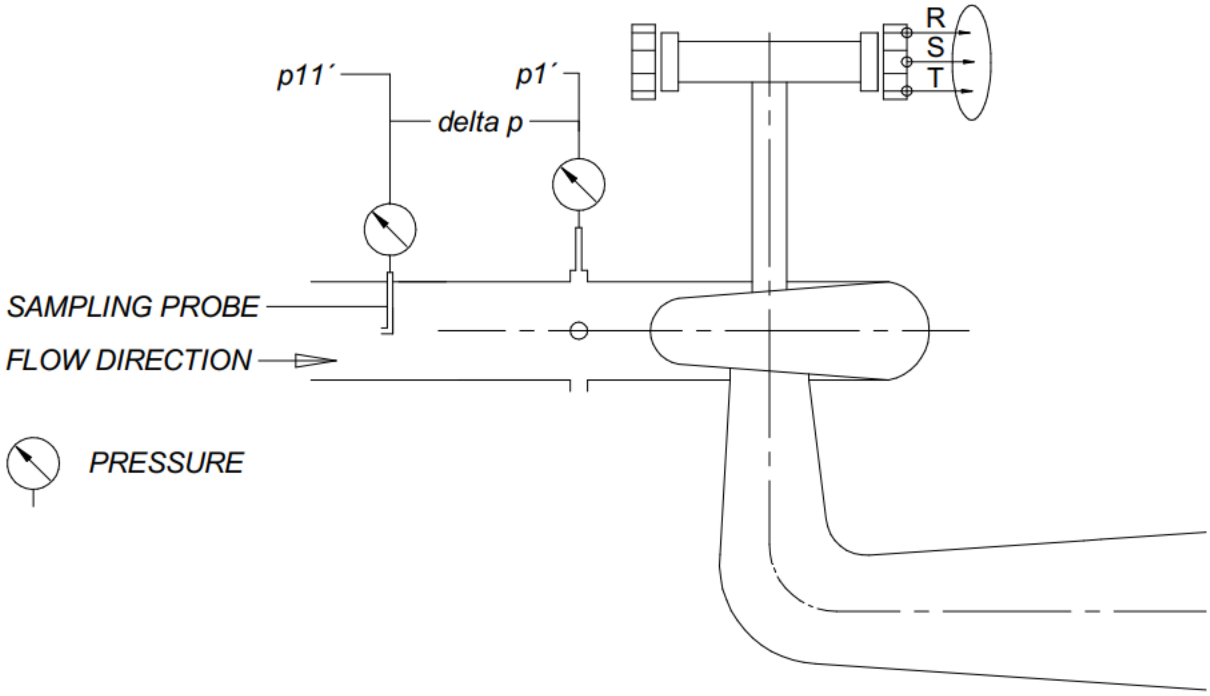

Figure 3: Sketch of the measuring setup

Further we present the results of four case studies comparing the relative flow measured by the Pitot to the reference discharge Q_{ref} that is provided by the thermodynamic method.

Two different approaches for the calculation of the main turbine flow Q were employed.

First, the (local) fluid velocity v that is delivered by the Pitot principle is directly used to estimate the global flow Q by applying it to the entire area A of the conduit's section at the probe's location

$$Q = v \cdot A$$

Equation 3

This approach (further named "Pitot") is ignorant of the fact that the velocity is not constant across the section. In fact, a boundary layer close to the conduits walls is present where the velocity is lower than in the centre of the conduit. Depending on the flow profile and the position of the probe's head in the conduit this method could lead to significant errors.

To better estimate the flow a second approach is applied, inspired from the calculation of the flow by the Winter-Kennedy method. This method assumes that

$$Q = c \cdot \Delta p^n$$

Equation 4

where the constant c and exponent $n \approx 0.5$ must be determined by reference measurements. This is done graphically by noting the logarithms of reference measurements for Q and Δp in a plot with logarithmic axes. As reference for calculating c and n the flow Q is used that can iteratively be calculated from the measurements of the thermodynamic method. Results from this approach are further named "exponent / constant". It should be noted that the calculation of c and n by that method is not completely determined. If more than two reference points exist and not all points align perfectly, the analyst must choose a fit that deems to give the best results. This can affect the comparison with the reference flow and with the Pitot calculation method.

2. Case studies and results

Francis machine with spherical main inlet valve and nominal head $H = 260\ m$

For this case study the measurement section for the static pressure p_1 and for the installation of the sampling probes is situated downstream of the spherical main inlet valve. Relative deviations between reference discharge and calculated discharge are in a range of $-2.3\,..\,1.5\%$. Only measurements close to the optimum of the hydraulic machine are available i.e., between 80% and 100% of the nominal power output.

Both methods of calculating the main flow Q based on the additional pressure measurements show significant deviation from the reference Q. The Pitot method has the biggest total error. The points related to the exponent / constant method are the same as the Pitot method's points rotated clockwise around the point at $P = 100\%$. Therefore, the sum of errors and the highest deviation are lower for this method. The rotation results from choosing an exponent $n \neq 0.5$. This allows to better match the flow-pressure relation to the reference. In this case $n = 0.5295$ was found to best match the reference flow.

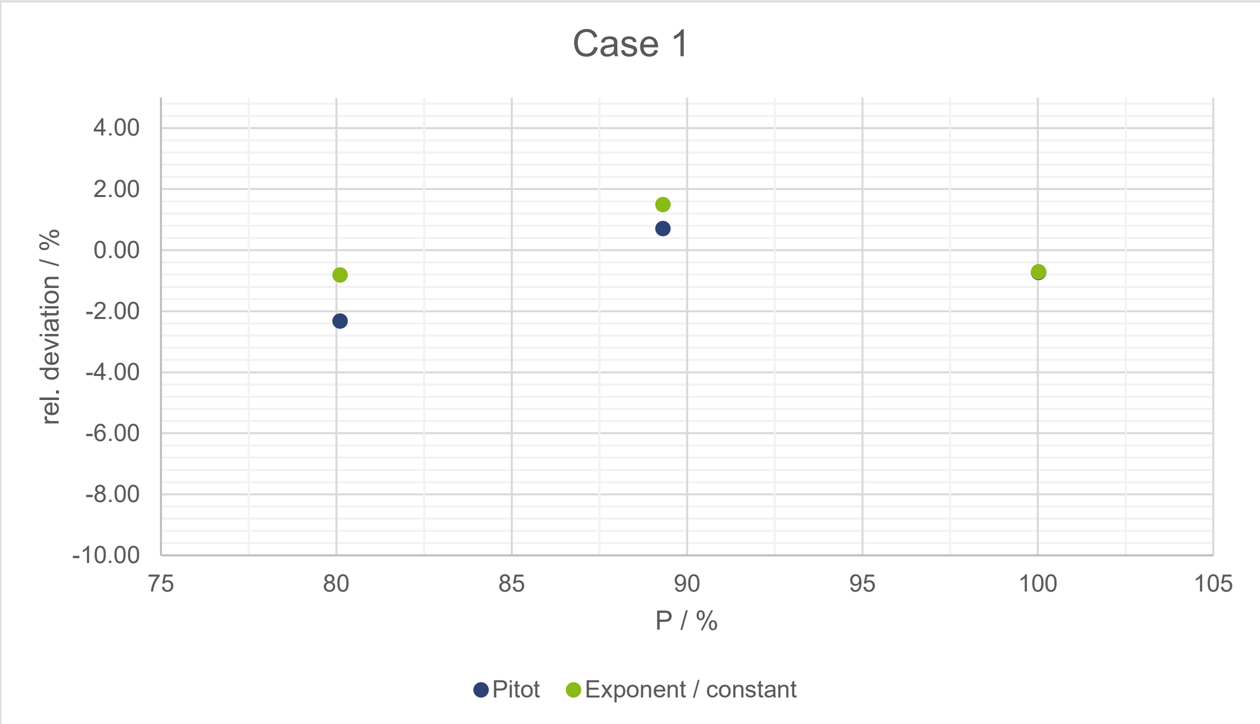

Figure 4: Comparison of case study 1

Francis machine with butterfly-type main inlet valve and nominal head $H = 115\ m$

This case study is performed on a power unit which is isolated from the head water by a butterfly-type main inlet valve. The reference section of the turbine inlet is again located downstream of the MIV. The disc of the butterfly valve remains in the flow when the valve is open and therefore induces a pressure drop and an irregular velocity profile downstream. This is a big challenge for the thermodynamic method. With the nominal head already close to the limit of applicability of the thermodynamic method, the dissipation due to the disc and the irregular and time-varying velocity distribution make it difficult to reliably estimate the specific energy of the main flow in the inlet section.

To further exacerbate the measurement conditions, the reference section is located only $0.85\ d$ from the MIV centre (d being the diameter of the butterfly-disc).

Figure 5 shows the relative deviation of the two pressure-based flow values from the reference flow as obtained by the thermodynamic method. The deviation is as high as approx. -7% for the Pitot method and approx. -2.5% for the exponent / constant method. Here the points of derivation are rotated about the $P = 90\%$ point between the two methods. This is the result from selecting the exponent $n = 0.5421$ which optimized the match between the exponent / constant flow and the reference.

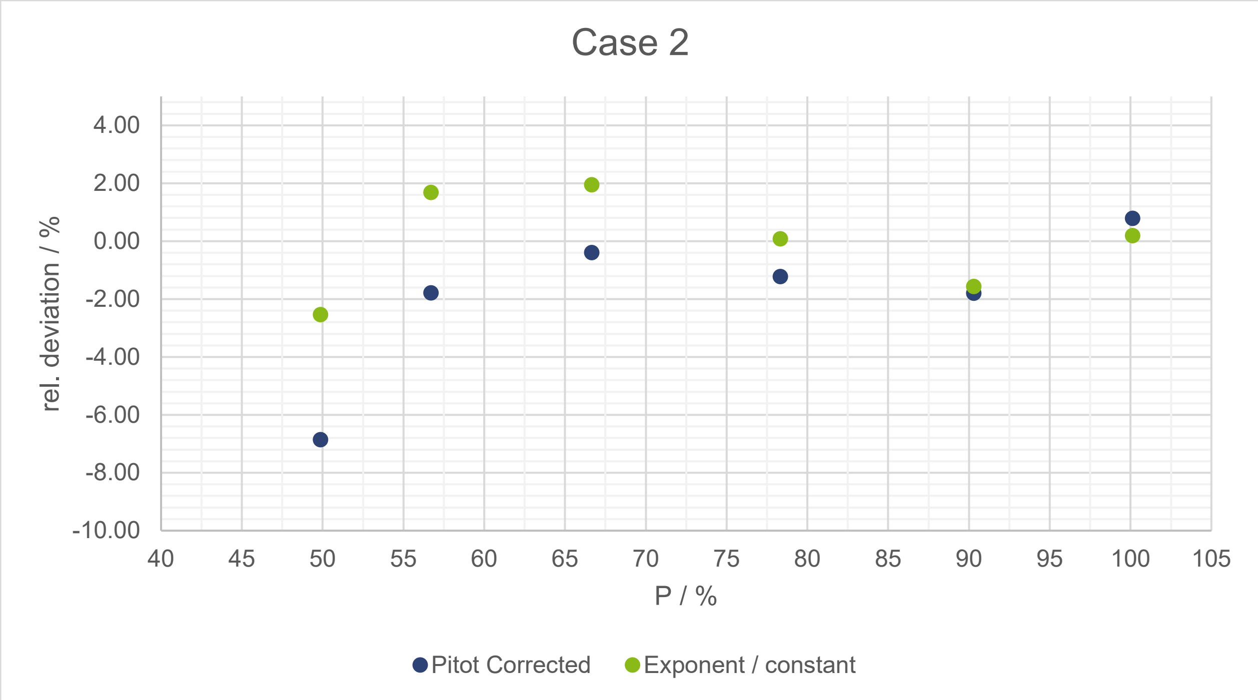

Figure 5: Comparison of case study 2

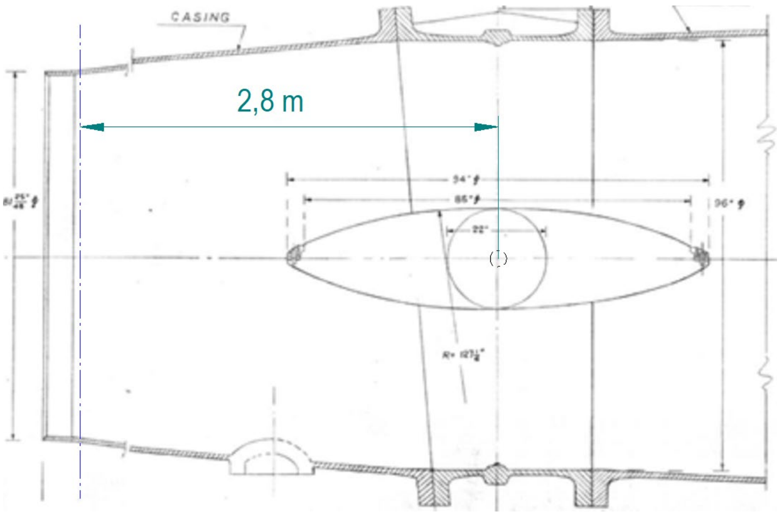

Figure 6 Location of the valve body to the measuring section

Francis machine with spherical main inlet valve and nominal head $H = 365\ m$

This study is performed again on a power unit equipped with a spherical main inlet valve. Therefore, no influences from the valve must be feared and compensated. The relative deviations between reference discharge and calculated discharge are in the range of $-3.2\,..\,2.4\%$. Again, the Pitot method exhibits the largest error. The rotation of the exponent / constant points is much weaker in this study, and it is in the counterclockwise direction. The exponent is $n = 0.4959$ very close to and smaller than 0.5.

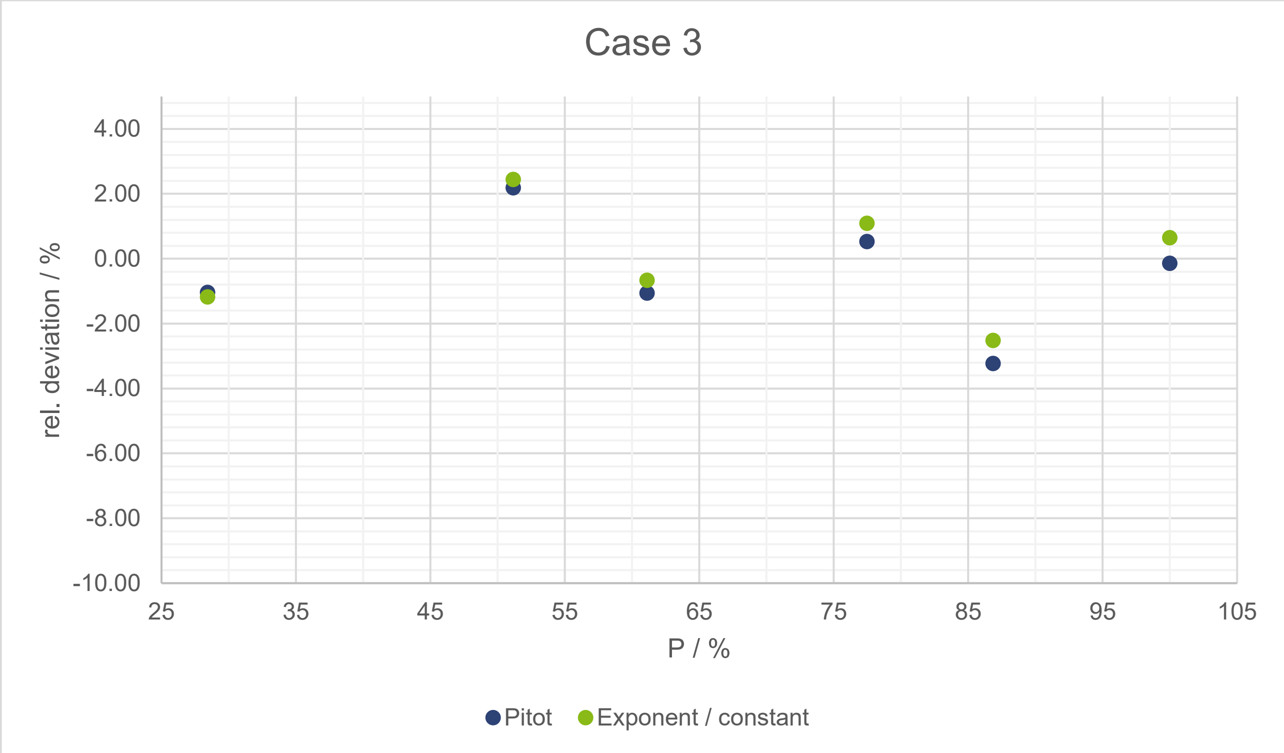

Figure 7: Comparison of case study 3

Francis machine with spherical main inlet valve H=277m

At case study no. 4 the measurement the section for the static pressure p_1 and for the installation of the sampling probes is situated downstream of the spherical main inlet valve. For the exponent / constant method the relative deviations between reference discharge and calculated discharge are in a range of $-1.86 \ldots 1\%$. The exponent is 0.486 and the constant 0.856. The pitot method results in a deviation range between $-4.8 \ldots -1.4\%$.

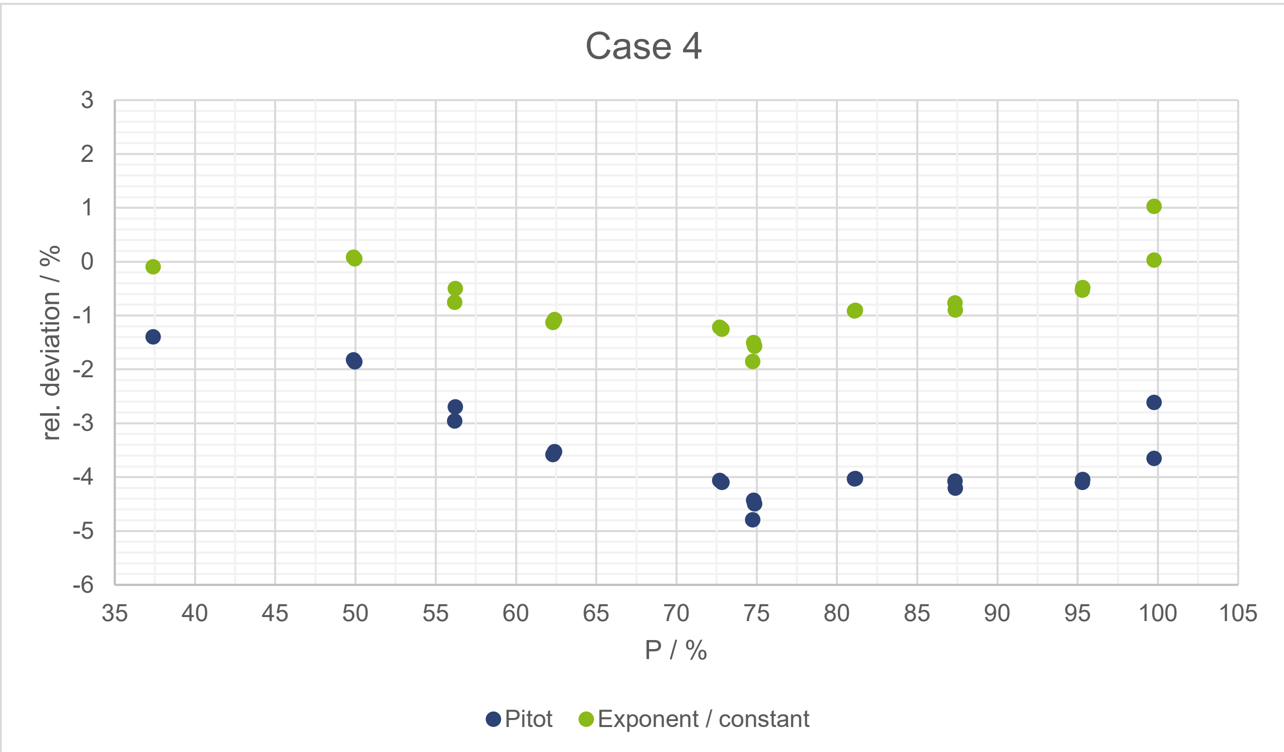

Figure 8: Comparison of case study 4

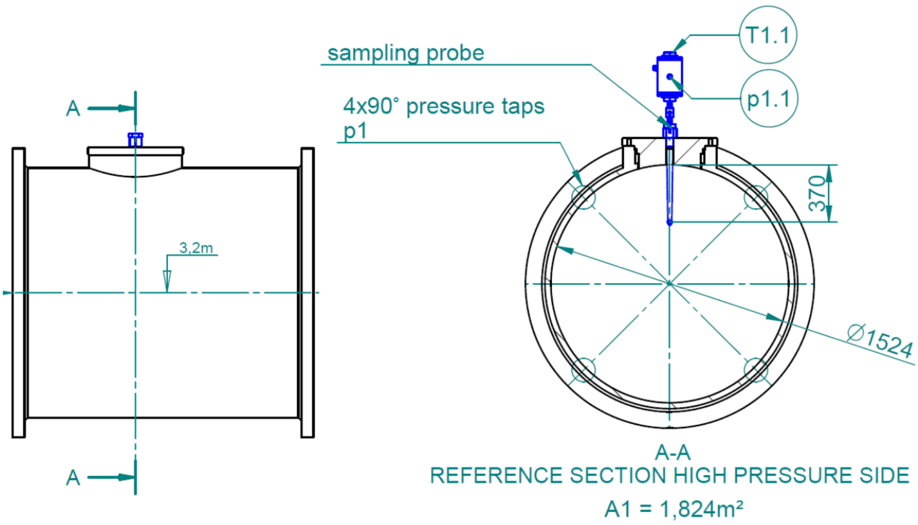

Figure 9 Sampling probe and static pressure taps location

3. Conclusion

The intention of the performed investigation is to examine a possibility for a relative flow measurement with the pitot principle with the usage of sampling probes.

Overall, four different case studies of power units with different head and flow rates are evaluated. All investigated power units are designed with full spiral cases and with flow velocities between $7\ \mathrm{m/s}$ and $14\ \mathrm{m/s}$.

Three out of four case studies show comparable results for applications with a sampling probe installation after the spherical valve. The deviations are in the range of $\pm 3\%$ to the reference discharge value.

Rel. Deviation from Q_{ref} [%]		CASE			
		1	2	3	4
Exponent/ constant	MIN	-0,82	-2,54	-2,51	-1,86
	MAX	1,50	1,96	2,44	1,03
Pitot	MIN	-2,33	-6,85	-3,22	-4,79
	MAX	0,70	0,79	2,20	-1,40

Figure 10: overview of relative deviations

Case study no.2 – with an installation after a butterfly valve – shows deviations in a range $-20..25\%$. Only with a correction of the inlet area similar results as in the other cases were achieved.

The approach by calculating an exponent and a constant works well for all case studies and especially for the installation after the butterfly valve better results are achieved.

It must be mentioned that in the case when this method should be used for a pure index test i.e., no reference flow is available, the constant and exponent need to be defined according to the indirect method. This approach is not presented in this paper.

In all cases it is possible to achieve flow rates in a good match to the reference value and usage for e.g., an index test at a Francis Turbine with full spiral case can be recommended after evaluating the four case studies. The described method can be recommended for Francis turbines with full spiral case only since that is the type of turbine represented by the four case studies.

In all cases it is possible to achieve flow rates in a good match to the reference value and usage for e.g., an index test at a Francis Turbine with full spiral case can be recommended after evaluating the four case studies.

For the mechanical installation it is recommended to use four pressure taps that connect to a manifold according to the IEC 60041 requirements. For the sampling probe it is required to align the stagnation point with the probe's orifice. A mark on the outer side of the probe can be helpful.

References

[1] ISO 3966 – Third edition 2020-07 – *Measurement of fluid flow in closed conduits – Velocity area method using Pitot static tubes*

[2] IEC 60041 – Third edition 1991-11 – *Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines*

[3] IEC 62006 Ed. 1.0. Hydraulic machines – acceptance tests of Small Hydroelectric Installations