Kirchbichl Unit 4 - Looking for efficiency permille and not seeing the missing percent

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1. Abstract

The existing Kirchbichl HPP, a diversion power plant on the river Inn with three Kaplan turbines, was erected in the 1940s. From 2017 to 2020, the facility underwent an expansion increasing the discharge by about 50 % with addition of a fourth unit. Numerical and physical assessments indicated a mediocre inflow condition to the new unit. However, due to project boundary conditions regarding land ownership and civil constraints, no other option was possible.

Following the initial commissioning tests conducted in 2020, it was determined that the efficiency of the unit was significantly below expectations. A test programme was unable to yield any significant improvement or insight into the causes of the poor efficiency. The manufacturer of the unit, VOITH HYDRO, and the operator, TIWAG, agreed to engage ETAEVAL to carry out flow measurement with current-meters, performed in 2023.

As anticipated, the inflow to the turbine is suboptimal, exhibiting transient fluctuations of the direction as well as the formation of vortices of different scales. The actual flow rate was measured to be below the value calculated from the unit's characteristic hill chart, namely a constant offset throughout the entire flow range. The measured efficiency was between 1 % and 4 % below the guaranteed values.

A new analysis of the data considering the offset in the calculated flow revealed that, shortly after the unit's start the efficiency was consistently nearby the guaranteed value. This state of good efficiency persisted for hours or even for some days before gradually decreasing to -10 %, a phenomenon for which no explanation could be found. A detailed investigation including the comparison with the plant downstream HPP Kirchbichl revealed that debris jamming in the guide vanes and the runner has a significant impact on the efficiency, much higher than expected. From the registered data, it was possible to extract the efficiency decrease due to debris. Regarding this, the measured efficiency agreed with the guaranteed values.

Neither manufacturer nor operator were aware of such a high impact by comparably small parts of debris in the bulb turbine. A flushing programme is currently under development with the objective of detecting the degree of blockage and decreasing efficiency during operation.

2. Project Extension Kirchbichl Unit 4

The Kirchbichl power plant underwent an expansion between 2017 and 2020, with the addition of a fourth unit. A channel of approximately 1 km in length runs from the reservoir in the river Inn to the power station's forebay. The extension required an approximate 30% increase of the plant forebay (**Fehler! Verweisquelle konnte nicht gefunden werden.**). Between the existing units and the new unit, an overflow separation pillar was constructed, which was determined to be the optimal solution under the specified boundary conditions during hydraulic testing. Nowadays unit 4 generates approximately 20% of the power plant's total annual production, amounting to 34 GWh, which represents about 20% of the power plant's total annual production of about 164 GWh.

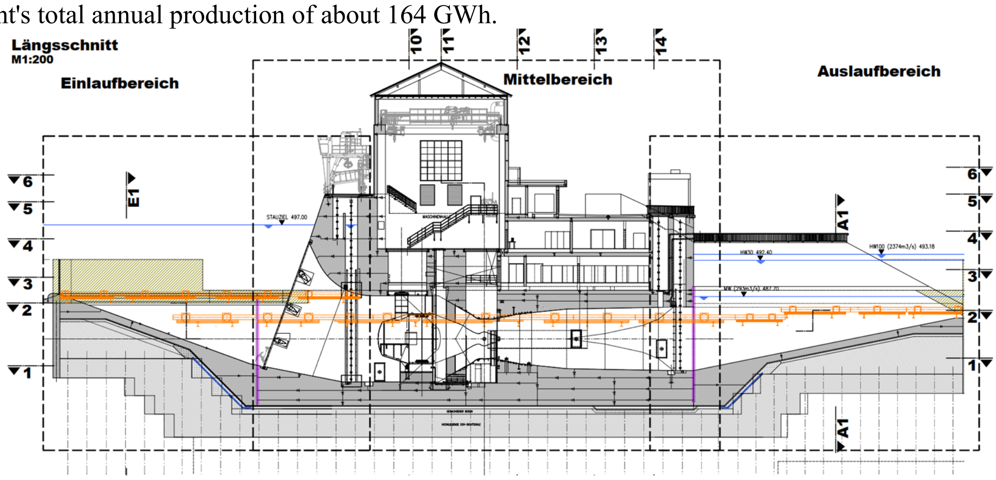

Figure 1 Cross Section of Unit 4

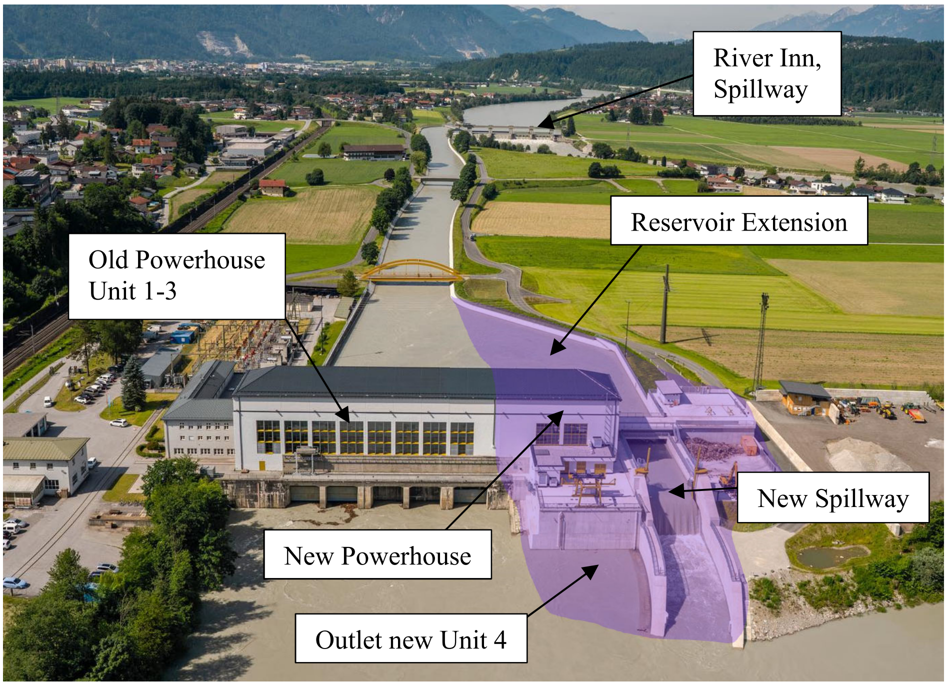

Figure 2 Kirchbichl plant overview

With the given constraints of limited space and unit 4 to be built beside the main flow of the channel, it was decided to perform a hydraulic model test in order to assess the inflow pattern and possibly install flow straighteners or pillars. This test was carried out during the project development phase with a variant study for the optimum design, considering different variants which included different pillar types and positions. The impact of the existing units to the inflow of unit 4 was also tested. CFD calculations were performed in parallel and compared with the model test results.

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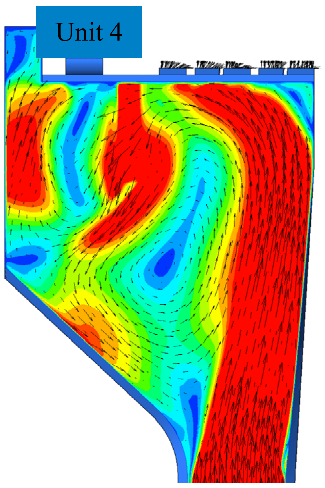
<td>
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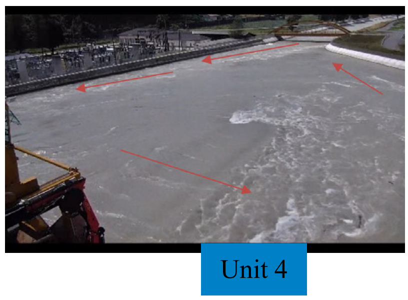
<td>
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<td>Hydraulic model test [1]</td>
<td>Simulation CFD [2]</td>
<td>Picture, Full load Operation Unit 4
200m³/s, 2021</td>
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Figure 3 Inflow patter to unit 4

The model test was based on the common practice throughout the hydro power business, which is mainly based on the definitions made by Fisher and Franke [3].

- No air vortex intake
- 80% of the measured velocities within +/- 15%
- Volume flow between the left and right side of the cross-section within +/- 5%
- Flow deviations between in the four quadrants within +/- 5%

The model test result and the numerical study showed acceptable results if only the newly built unit 4 is in operation. If other units are operated simultaneously, the specified criteria was missed and only the air vortex intake could be met. These results were part of the project specification and thus had to be considered by unit suppliers in the design and in guaranteed values.

The model tests furthermore showed clearly an asymmetrical, deflected flow towards the units, depending on the number of units in operation. The main flow runs to units 1 and 2 and is deflected by the powerhouse in front of them. A part of the deflected flow overflows the pillar perpendicularly to unit 4, whereby the main flow is diverted around the pillar and creates vortices of different scale.

In actual operation these effects were also observed, as large scale vortices remain for some seconds in front of unit 4, dissipate and reappear on different locations with possibly even different rotating direction. The deflection losses created a water level difference in the plant forebay of up to 40 cm from left (unit 4) to right (unit 1) riverbank.

3.1 Technical Data of Unit 4

VOITH HYDRO designed and delivered the bulb turbine as well as the generator for Kirchbichl unit 4. The units hydraulic design with all its parameters and performance values was derived from a model tested base model that has been used in several projects before and after Kirchbichl. The unit has the following main data:

H_{rated} = 9,7 m
Q_{max} = 200 m³/s
n = 100 rpm
$P_{Generator}$ = 20 MVA

A four blade runner design was found to be best suitable for the given hydraulic data. A challenging part of the mechanical design was the stiffness and resonance frequency of the bulb, with the boundary conditions according to good inflow and requested generator inertia.

3. Performance gap

The unit was commissioned in 2020 and put in commercial operation up to full load from 2021 onwards. Operational data is constantly monitored and stored with a sampling rate of one second. This acquired turbine data includes power, head, runner position, guide vane position, bearing and shaft vibration, bearing temperatures and hydraulic pressures. After several weeks of operation, the initial data was analysed with the conclusion that the performance of unit 4 failed to meet the expectations regarding efficiency by up to 10%. At that time, it was unclear whether the losses occurred in the water way, the turbine, or at the generator.

A test programme was set up in collaboration with the unit supplier, VOITH HYDRO. Given that the assumed loss was up to 1 MW and that the temperatures in windings and stator were within an expected range, it was concluded that the electrical unit cannot be the source of the issue. A meticulous examination of all current and voltage transformers, the level measuring points and pressure sensors in the drive water path revealed that measurement errors or systematic errors due to wrong setup or installation were not a relevant factor either. The considerable magnitude of the discrepancy furthermore showed that measurement uncertainties of the relevant sensors are also not the key issue of the problem. Thus, the sole indirectly acquired parameter was the flow rate of the unit which is determined in two ways: firstly, by means of a back calculation based on the measured head and the position of the guide vane and runner, as indicated in the characteristic diagram; and secondly, by a Winter-Kennedy / differential pressure measurement on the bulb of the unit. The coefficients of the differential pressure measurement were determined by the manufacturer in the model test and then scaled up to the prototype unit. It was observed that the differential pressure measurement was not capable of continuous monitoring due to permanent accumulation of air in the piping system. The static pressure value gradually declined particularly at full load, which resulted in a distorted differential pressure / flow value. To address this, a continuous venting system was implemented before and after each measurement to maintain a stable pressure environment.

The following diagram illustrates the representative range of efficiency achieved in 2022 in comparison with the target efficiency (left). The diagram on the right depicts the time curve of the efficiency deviation from the target (etaDIFF), the generator output (PG), flow rate (QTU), position of the guide vane (LE) and runner (LA). The efficiency is calculated as follows:

$$\eta_{TU} = \frac{P_G}{\rho * g * H_{net} * QTU} * \eta_{GEN} * \eta_T \tag{1}$$

Mechanical losses in the bearings were considered in the guarantee. Transformer and generator efficiencies, were taken from the manufacturer's specifications and were confirmed in corresponding acceptance tests. The turbine flow rate QTU remains as the only parameter which is not directly measured.

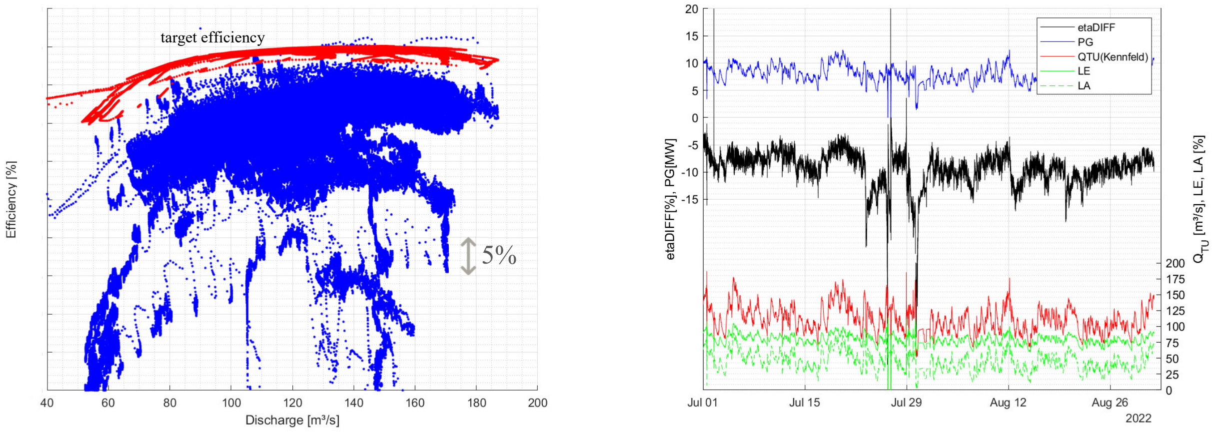

Figure 4 Efficiency Curve, July – September 2022

Figure 3 shows that the efficiency deviation over time is, on average, -10%. However, there are instances where it can improve or deteriorate by 5% in a relatively short period of time. This phenomenon can also be observed in the characteristic curve, where the scatter band is up to 10%, with the average deviation also approximately -10%. It is noteworthy that the deviation across the entire flow band reaches a similar absolute value. It would be expected that losses from the flow or due to vortex intake would show a certain dependence on the flow rate or speed; however, this is not the case.

A wide variety of investigations have been carried out over the course of the operating time to date. The following list summarises the most important findings: To ascertain whether the efficiency was affected, tests were conducted with the additional operation of the three older units, as well as with unit 4 operating only. The results demonstrated that this did not have a significant impact.

Influence of the overflowed pillar:
Even though the hydraulic model tests have already shown that a deterioration of the inflow is more likely to be expected with non-overflowed piers, a test was carried out with a lowered level. For this purpose, the level in the forebay was lowered below the upper edge of the pier and operated with unit 4. The flow in the forebay changed, but this had no major influence on the efficiency of unit 4.

Figure 5 Operation with lowered head water level

Geometry Check of the Runner:
The entire runner geometry was scanned by VOITH HYDRO using 3D laser scanning. This measurement was carried out in different positions in order to check the correlation of the indicated opening as well as the runner / blade geometry in general. The results of the scan were compared with the 3D model. Both the hydraulic contour and the absolute positions showed virtually no deviations compared to internal or IEC standards.

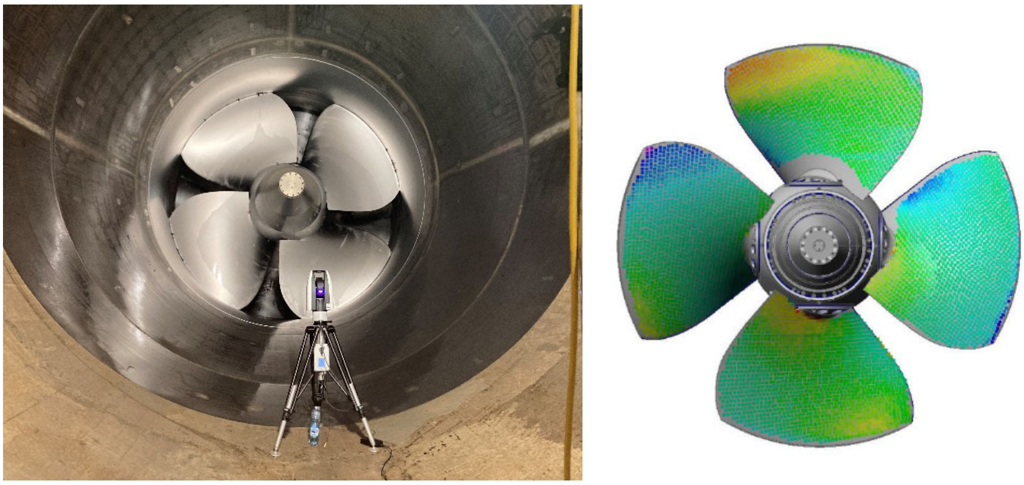

Figure 6 3D Scan and comparison to nominal design values

Index Testing:
Two index measurements were carried out during the investigations. The resulting propeller curves showed a optimisation potential of 0.5 to 1% which is also below the missing range. The desired difference is many times higher, which is why the correlation between runner and guide vane has not yet been adjusted at this point in time.

Air Accumulation in Water Way:
Due to air pockets in the intake manifold, it is conceivable that the energy recovery, the conversion of kinetic energy into potential energy by expansion, is disturbed by detachments. However, several shutdown procedures and observations in the turbine outlet as well as in the upstream gate slot (air accumulated in front of the turbine would also be conceivable) gave no indication of such air accumulations.

Check for Correct Discharge:
As the now permanent direct flow measurement is installed in low-pressure turbines, discharges from upstream and downstream gauging stations were compared. A comparison turned out to be difficult due to the transient discharge conditions in the natural course of the river and the temporal shifts. When only units 1-3 were operated, the discharges matched the measured discharges upstream and downstream. If only unit 4 was operated, the measured discharges showed a value that was approx. 10 m^3/s lower. This gave a decisive indication that the indicated flow at the unit panel of the turbine cannot be correct.

4. Efficiency Measurement

The efficiency measurement was conducted by etaeval GmbH. Twenty-four OTT C31 propellers (A-Type) were mounted on a vertically movable frame, which was then adjusted vertically in the gate slot. Two displacement methods were employed: stepwise and continuous [4]. Two different methods, namely acc. ISO 3354 and a difference method [5], were used for evaluation. Additionally, six angle sensors were affixed to the crossbeam of the frame, enabling the measurement of cross flows in a horizontal direction. Subsequent to the volume flow measurement, a correlation measurement was conducted utilising the calibrated differential pressure measurement. The ensuing results may be derived from the measurements.

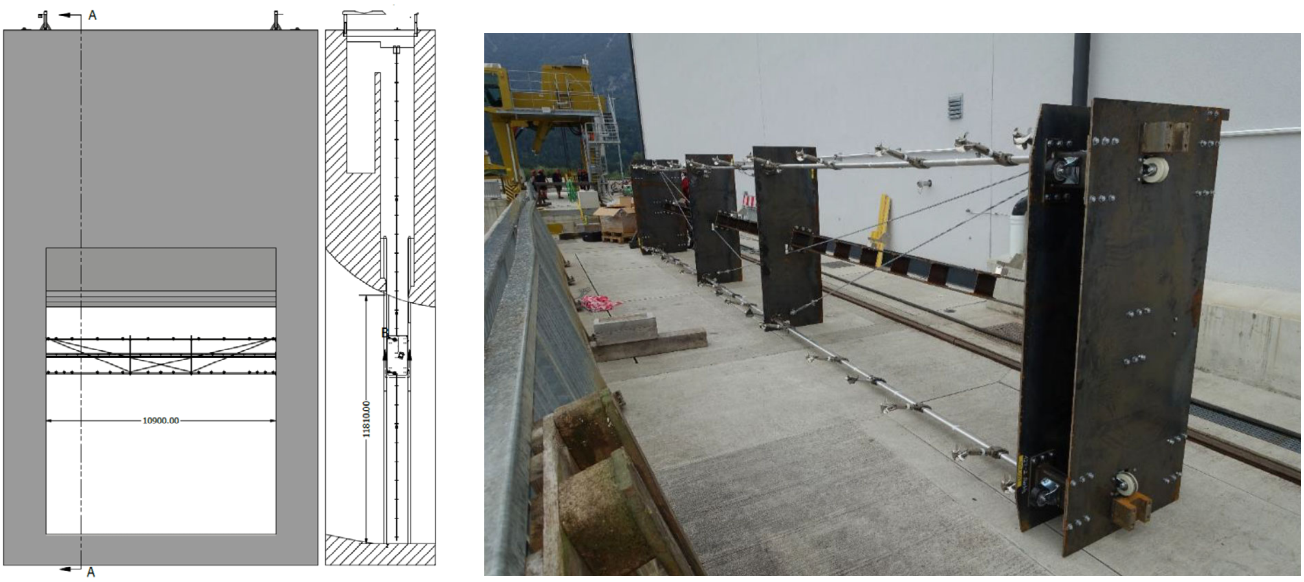

Figure 7 Measuring Section and steel frame with sensors

Figure 8 Angle sensor at measuring frame

Results and findings of the propeller measurements were summarized as follows:

Efficiency measurement:

- The measured efficiency is on average approx. 3% below the guaranteed values.
- The measurement uncertainty was determined to +/-1.3%.
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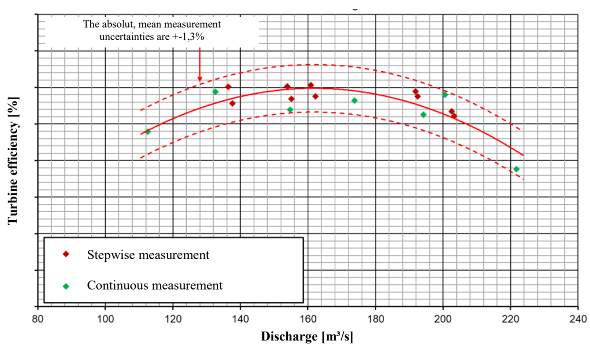


Figure 9 Results of the efficiency measurement [6]

Cam Correlation check (runner / gate):

- The cam correlation of runner and gate position can be optimized.
- The potential for optimisation was identified between 0.2% at minimum load up to 0.9% at maximum load.

Flow measurement:

The actually measured flow rate is generally-7.5 m³/s lower than the value indicated at the governor over the entire discharge range.

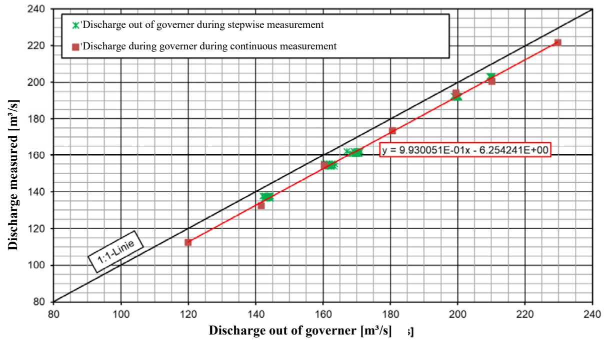


Figure 10 Flow measurement vs. governor value [6]

Inlet flow – velocity distribution and angle:

The measurement was evaluated with regard to the above-mentioned inflow criteria, which was also used for the model test evaluation. The criteria could not be met, which indicates a sub-optimal inflow pattern.

The discrepancy between the actual and target efficiencies was attributed to the suboptimal inflow in comparison to the inflow criteria of Fischer-Franke [3]. The measurement showed asymmetric inflow fields which could not be directly evaluated according to its efficiency impact. Thus, an ideal CFD model was set, which only shows the inflow field induced by the intake of unit 4. The CFD with the ideal model was performed to evaluate the impact of the pillar and the asymmetrical forebay.

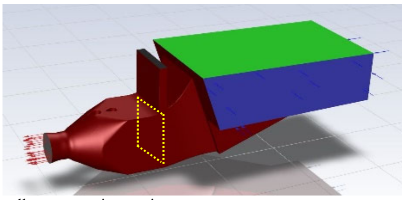
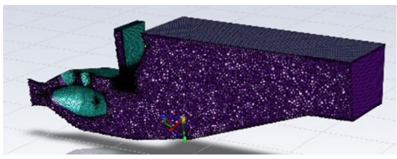
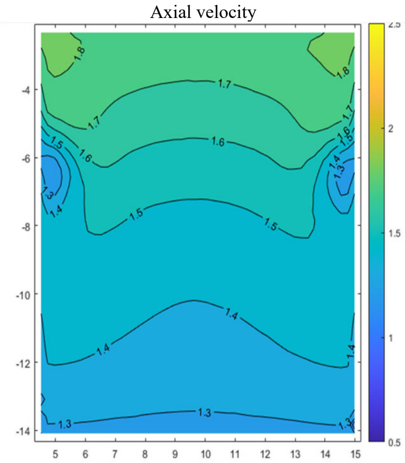
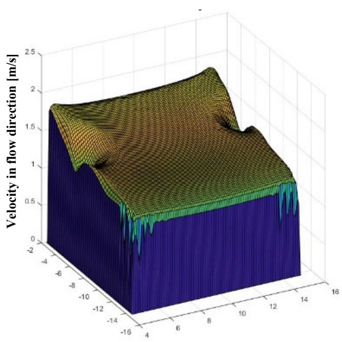
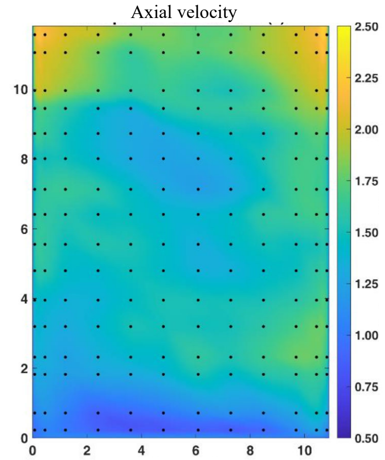
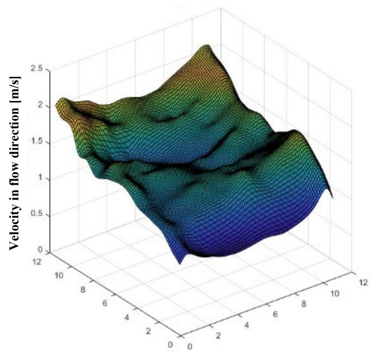
CFD Model	CFD results	Measurement results etaeval
 yellow: measuring section  **Simulation Details:** Ansys Fluent 2022 R2 Mesh: Fluent mesher, poly-hexcore Turbulence model: k-ω SST Mass-Flow outlet, pressure inlet carried out by TIWAG [7]	  	 

Figure 11 Comparison of measurement and CFD of a symmetrical inflow without pillars [7]

The results show that neither the ideal CFD model nor the measurement did fulfill the criteria according velocity conformity. Figure 12 shows the relative deviation of the single velocities to the mean velocity in the measuring section. The curve “area correction” refers to a discretized flow field derived from the raw data with unequally spaced propeller positions and measuring levels. This allowed for an equal weighting factor of every point. Even if the deviation is smaller, the velocity distribution of the ideal model cannot fulfil the criterion either.

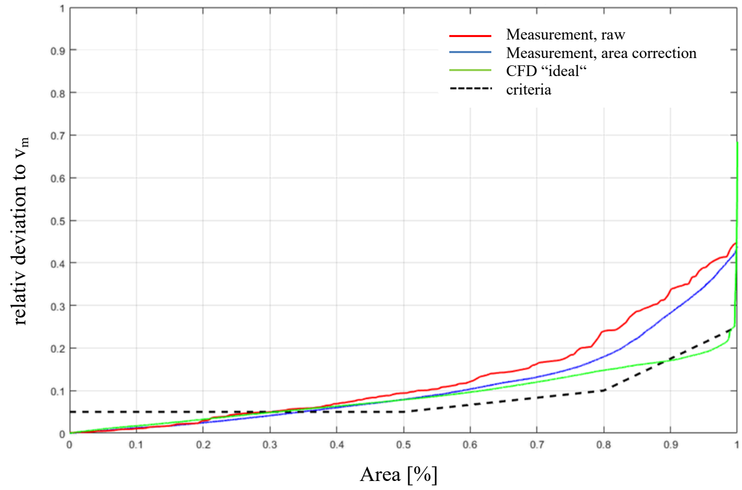


Figure 12 Fisher-Franke criteria, CFD vs. measurement

The measurement (Figure 13) shows that the criterion of 80% of all measured velocities within +/- 15% was not met. The CFD with the ideal model did not fulfill the criteria, although with a different velocity distribution over the section. Therfore, the numerical analysis suggests that this criterion cannot be met even under ideal inflow conditions and the bulb turbine alone creates asymmetries higher than specified.

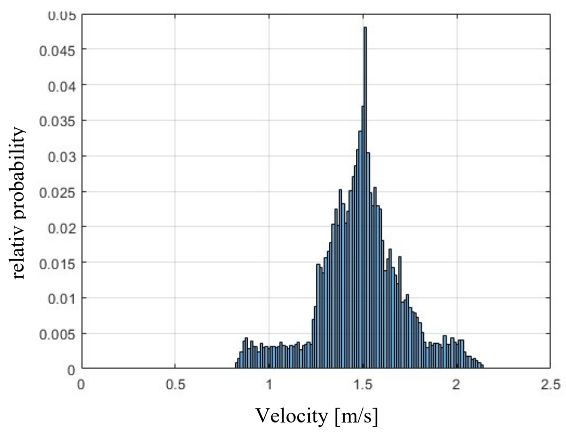
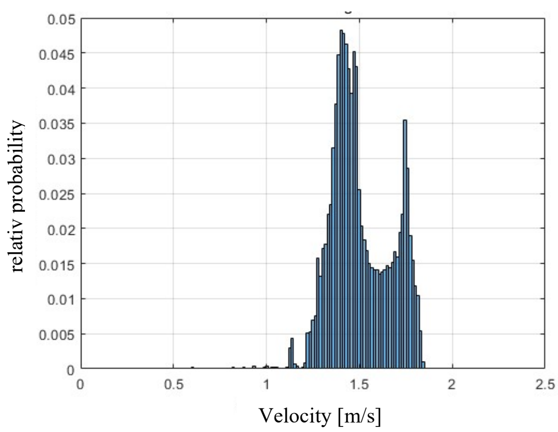
Measurement at 200 m³/s, only unit 4 in operation	CFD „ideal“
	
Average velocity: 1,486 m/s Median velocity: 1,492 m/s v_{avg} -15%: 1,263 m/s v_{avg} +15%: 1,709 m/s **probability +/-15%: 74,1%**	Average velocity: 1,445 m/s Median velocity: 1,461 m/s v_{avg} -15%: 1,228 m/s v_{avg} +15%: 1,661 m/s **probability +/-15%: 75,5%**

Figure 13 Probability distribution, CFD vs. measurement

Angle of the flow:
The angle sensors have allowed for monitoring the horizontal main flow direction as well as the occurring fluctuations. The angle sensors had little damping and were directly exposed to vortices. However, the angle signals fluctuated in a range of +- 20° in some areas of the inlet. Especially in the upper part of the section, fluctuations were constantly high at the whole operating range of unit 4.

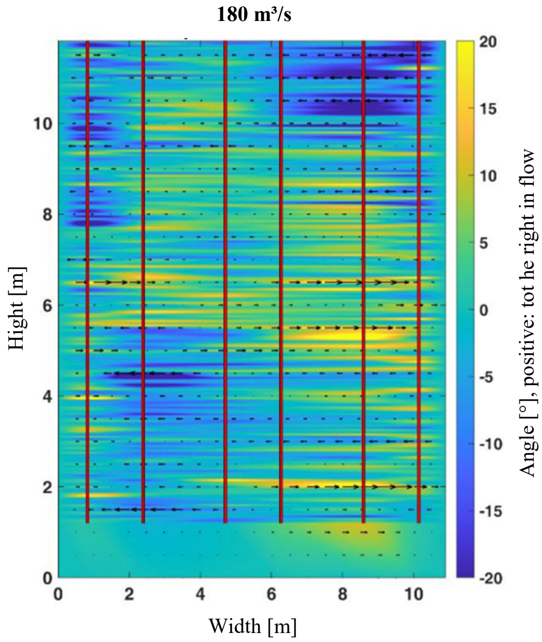


Figure 14 Horizontal flow direction angle at measuring frame

Finally, the efficiency measurement confirmed that the efficiency of unit 4 was lower than the guarantee. However, the discrepancy turned out less pronounced than anticipated, as the flow rate also does not align with the characteristic diagram. Nevertheless, a clear cause for the considerable efficiency discrepancy could not be detected, based on the data acquired during the efficiency measurement.

5. Final Assessment and Solution

All above – mentioned assessments and checks, numerically, experimentally and site tests did not answer the question why the unit's efficiency did not correspond with the model test results although a large data set has been acquired over the time. However, taking one step back and have greater view on the data finally lead to the solution.
It was observed that there were few intermittent periods during which the efficiency was within the guaranteed range. Subsequently, within a few days, there were instances of shortfalls in the range of 5 to 10%.

This phenomenon has been previously documented and became evident by postprocessing the long-term data.
Using the efficiency test results to correct the turbine flow by 7.5 m3/s, showed that the efficiency was close to the guarantee value during these short periods.

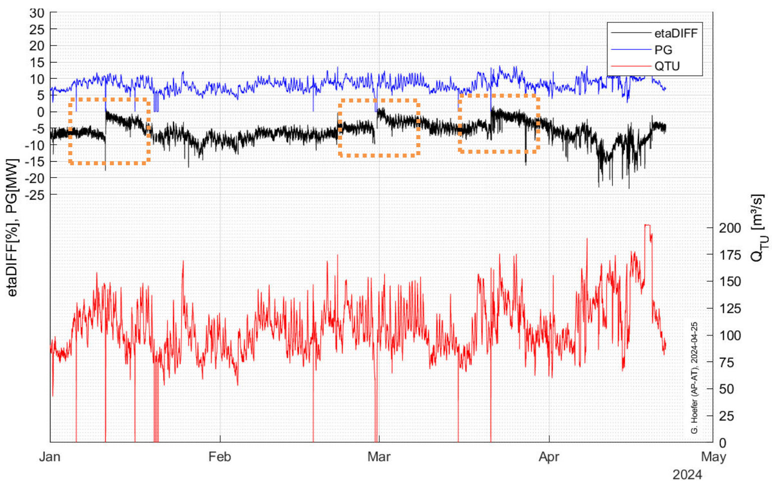


Figure 15 Efficiency deviation over Time, Jan – May 2024

In the aforementioned evaluation, which spanned the period from January to May 2024, the unit was deactivated on three occasions. Following each start of the unit, the deviation from the target efficiency is almost 0%. During the following days the deviation gradually became bigger until the next unit shut down. During the operational phase, self-healing effects are observed on numerous occasions, typically resulting from significant fluctuations in output within a relatively short timeframe. Such occurrences result in an immediate improvement of the efficiency, but does not fully reset to its nominal status, like it happens in the case of a unit shutdown.

The similar plant Langkampfen (completed in 1998), situated a few kilometers downstream which also comprises of bulb units has also been analyzed according its long term efficiency behavior. The results showed a very similar outcome like Kirchbichl unit 4. Langkampfen has an automatic flushing procedure that initiates a flushing process through off-cam operation (runner guide vanes) in the event of a significant discrepancy between the target and actual output. Similar to Kirchbichl, the improvement in efficiency is clearly evident, although not to the same extent as from a complete shutdown.

Assessing photo documentations showed flotsam, such as small branches and leaves around guide vanes and runner blades. This flotsam is mostly removed during the shutdown procedure and thus an inspection of the waterway does not show these parts every time. However, after assessing photos and inspection reports the reduction in efficiency could be attributed to this fouling from flotsam, such as small branches, leaves, etc. The trash rack spacing is 85 mm, which only prevents larger debris from entering the waterway. The significant impact of this flotsam has also been described by Staubli and Abgottspon [9].

Figure 16 Guide vanes (left) and runner gap (right) during inspection 2021 [8]

6.2 Influence during the efficiency measurement

Prior to the efficiency measurement, the unit was shut down for several days due to flooding. Consequently, the initial efficiency values observed at the outset of the measurement period were likely artificially elevated, and these values subsequently declined over time.

The subsequent diagram illustrates the temporal evolution of the efficiency deviation during the measurement campaign. It is evident that the efficiency has exhibited a continuous decline over the measurement period, following an initial period of elevated values. The individual measuring points derived from the step-by-step and moving-frame methods are represented in purple.

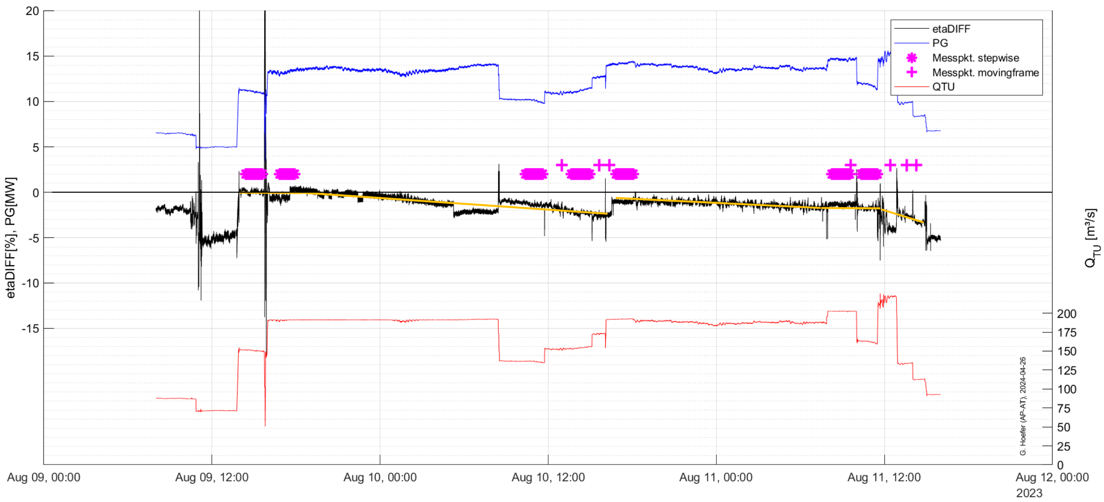


Figure 17 Soil impact during efficiency measurement

Correcting the gradual efficiency drop during the propeller measurement shows that the curve's characteristic is corresponding to the guarantee. If the measurement tolerance and the abrasive wear at the runner gap and at the runner leading edges are taken into account, the unit fulfills the guarantee values.

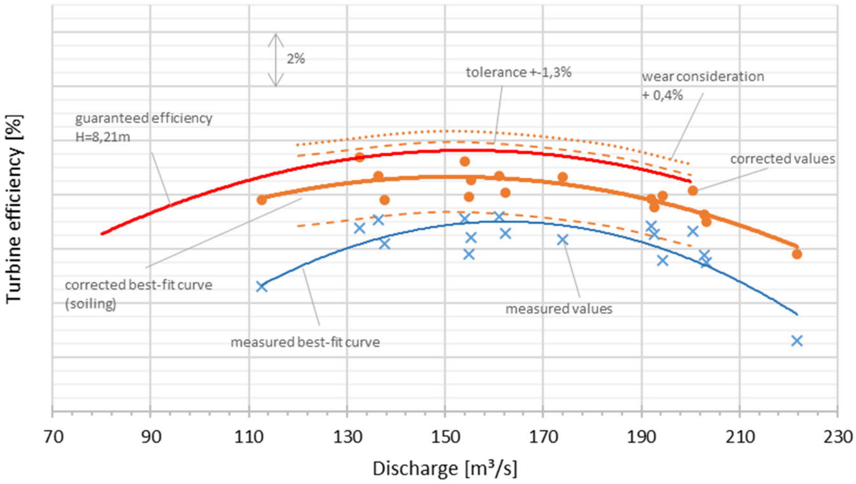


Figure 18 Efficiency over Time during efficiency measurement in Aug 2024

6. Flushing Test

A comprehensive overview of the subject matter can be found in the article "Verschmutzung von Kleinwasserkraftwerken", authored by Staubli and Abgottspon in 2010 and published by the Federal Department of the Environment, Transport, Energy and Communications [9]. This study, although focused on small hydro units gives a good overview of the impact, similar to the observations of Kirchbichl and Langkampfen. In the course of the tests, six different rinsing programmes were examined and analysed in advance using numerical methods (CFD). The variants that yielded the most effective flushing results were as follows.

1) guide vane and runner at 15%, then guide vane fully open and runner at 50%
2) guide vane at 10%, runner fully open

It can be concluded that the flushing effect of variant 1) is primarily attributable to the initial phase, wherein the guide vane and runner are positioned close to their respective limits. The efficiency of the flushing process is primarily determined by the position of the runner. One disadvantage of flushing variant 2) is that increased bearing loads are to be expected.

In the initial trial, both the runner and the guide vane flushing were subjected to analysis. In automated operation, it is of paramount importance that the flushing process does not disrupt the level control of the power plant. Should the flow rate through the unit be altered for an extended period, the headwater level will fluctuate, potentially leading to oscillations due to counter-regulation of other units. In such instances, manual intervention by the plant staff may be required. Therefore the turbine controller is locked during the flushing programme in order to ensure constant conditions. Therefore the flushing program should be completed in a short time to prevent significant changes in the level.

Operation outside the optimal correlation can result in increased vibrations, axial load reversal of the runner (approaching the counter track of the thrust bearing) and vortex pigtails in the intake manifold. It is also possible that reverse power (motorised operation of the unit set) may occur in certain conditions. This is a less significant issue from a mechanical standpoint, but it can potentially lead to unanticipated interactions with the grid operator.

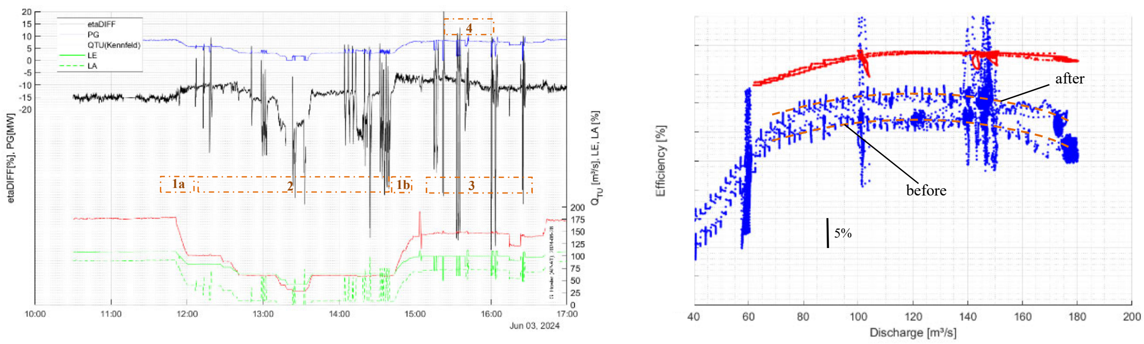


Figure 19 Efficiency over Time during efficiency measurement in Aug 2024

Ad 1a) The significant change in capacity from approx. 190 m³/s to 100 m³/s resulted in a noticeable improvement in efficiency of approx. 5%.

Ad 2) With very low opening of the guide vane of up to 40%, the runner was opened up to 100% several times in a short time. In some cases, a return power of up to 1.8 MW was achieved. The vibrations were greatly increased. However, a noticeable improvement in efficiency was not achieved.
Ad 1b) The renewed increase in output from approx. 75 m³/s to 150 m³/s again resulted in a significant improvement of approx. 5%.

Ad 3) At a runner position of approx. 70%, the guide vane was opened to 110% and also closed to up to 50%. A noticeable increase in performance could only be achieved to a limited extent, The efficiency increased by approx. 3%.

Ad 4) During the tests, the automated cleaning unit began to clean the inlet screen on unit 4. It was clearly evident that the efficiency dropped by several percent with each cleaning stroke. The cleaning of larger floating debris probably loosened smaller branches, which then travelled through the screen to the unit.

Overall, the flushing programme increased the efficiency by approx. 5%. However, it cannot be ruled out that this was mainly caused by the strong changes in the unit's performance rather than by the transient movements outside the context.

7. Conclusion

Kirchbichl unit 4 showed a significant lack of efficiency after commissioning which resulted in a comprehensive assessment campaign. The original hypothesis was a severe impact of the inflow conditions which were proven to be very unfavourable by model test and analytical criteria. CFD calculations showed that even a straight inflow without pillars has a velocity distribution which would not meet the Fisher Franke criteria. This criteria should be subject of further investigations for bulb turbines since it may only be achievable with very long intake channels.

After a step-by-step exclusion of several influencing factors and an efficiency measurement with the propeller method, the analysis of the long-term operating data showed a large time scale gradient of the efficiency.

The efficiency difference correlated with increased vibration values and finally was clearly attributed to clogging of guide vanes and runner blades. The normalized efficiencies that consider clogging and wear, finally are within the guarantee.

It is assumed that river flow bulb turbines comprise this effect frequently, which may remain undetected in case of only minor efficiency deviation. Thus, a clear optimization potential can be identified from an owner’s perspective and a focus on efficient flushing procedures should be taken.

8. References

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