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To cite this article: K Kubo *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **240** 022054

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CFD-based rehabilitation for the high specific speed Francis turbine

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Abstract. This paper present about the CFD based rehabilitation project for high specific speed (over 300 m-kW) Francis turbine. The area of rehabilitation was Spiral casing, Stay vane, Guide vane, Runner, and restricted Draft tube (draft elbow). The main goal of this project was to increase the turbine efficiency at all operating range with high operational stability, low noise as well as high cavitation performance. On the development phase of this project was carried out with CFD only (without Model test) to reduce the time of development. On the first step of this project, the shape of all components was optimized to reduce the hydraulic loss and to increase the cavitation performance with steady state CFD. After that, the operational stabilities (ex. Pressure fluctuation) on the partial load and over load point were verified with unsteady CFD. Finally, the field tests were carried out to confirm the performance of new turbine. It was found that the new turbine has excellent performance in efficiency, power output and operational stability (vibration and noise) compared with existing turbine.

1. Introduction

Hydropower was regarded as the main source of power generation in the earlier time, and it is well known as one of the most clean, safe and sustainable source of power generation in the world. Despite of the growing demand for new hydro power plant construction to increase the hydro power in developing countries, most of the hydro power stations in developed countries such as Japan have been operated more than 30 years. After many years of operation, there are needs to replace the existing turbine or rehabilitation project [1]. Except for specific cases, the rehabilitation of a hydro turbine generally concerns rather old machines for which most of the components have a strong potential of improvement. It is therefore usual to take advantage of the technology progress amassed from the time of the initial machine, to consider all the possible improvements that could be done.

In this paper discussed about the CFD-based rehabilitation project for high specific speed (over 300 m-kW) Francis turbine. On this project, the optimizing phase are carried out by CFD only (without model test) and it is required to redesign the Spiral casing, Stay vane, Guide vane, Runner, and restricted Draft tube (draft elbow) in line with the latest technology to achieve higher efficiency, operation stability, cavitation performance at all operating range compared with the existing power station. Finally, the field tests are carried out to confirm the performance of new turbine.



2. Background of the rehabilitation project

The target hydro power station of this project is located in Nagano Pref. Japan. This power station consists of a unit of Francis type turbine with iron spiral casing and draft tube with single pillar. All components of this power station were constructed by other company, so that the details of components were unknown. Table 1 summarizes the main parameters of proto type turbine for target power station.

Table 1. Summary of main parameters of Francis turbine for target power station

Stationary parts		Runner	
No. of Stay vane	20	No. of runner blade	13
No. of Guide vane	20	Runner outer diameter (mm)	1820
Guide vane flow passage height (mm)	730		

Table 2 shows the main specification of this target power station and figure 1. shows the comparison between turbine efficiency of the existing turbine and guaranteed value. As can be seen in Table 2, the specifications of this power station were changed, that is, maximum discharge was decreased more than 17%, but maximum output was decreased less than 12%; therefore, the turbine efficiency must be increase at the all over the operating range. Moreover, the noise and vibration, which caused in the turbine operation, have to reduce or keep the same level as existing turbine because the target power station was built in the neighbourhood of private house. In general, the Francis type turbine with high specific speed has the problems of the vibration at the partial load. Therefore, the operating stability, especially the vibration, needs to be assessed in the optimizing phase in this project.

Table 2. Specification of target power station rehabilitation project

	Existing	New
Net head (m)	20.0	19.81
Maximum discharge per unit (m^3/s)	21.0	17.25
Maximum power(MW)	3.50	> 3.09

3. Process of the rehabilitation project

Figure 2 shows a typical process flow for the hydro power station rehabilitation project. Generally, rehabilitation project is divided into three main stages, i.e. the pre development stage, development stage and post development stage. Details of each stage for this project are discussed thoroughly below.

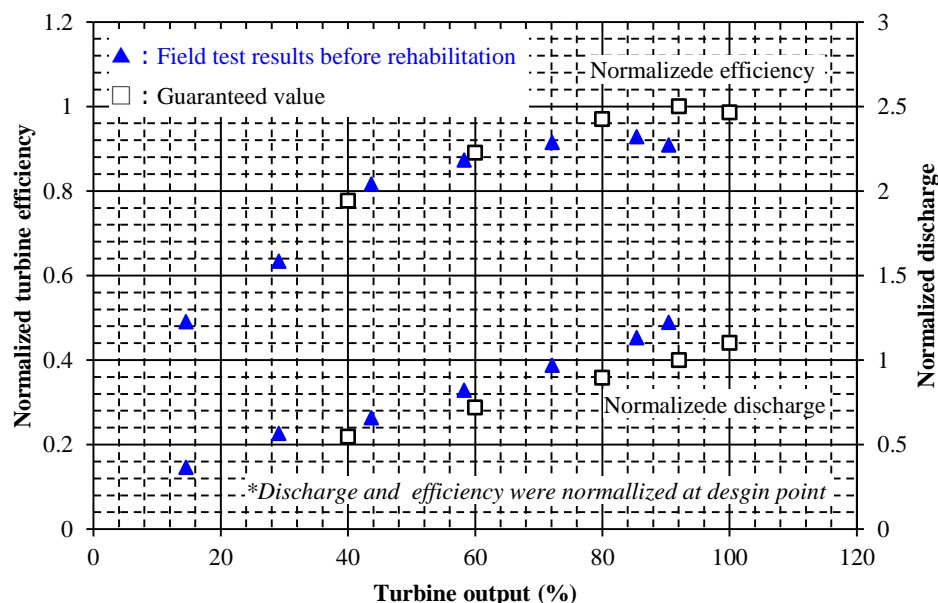
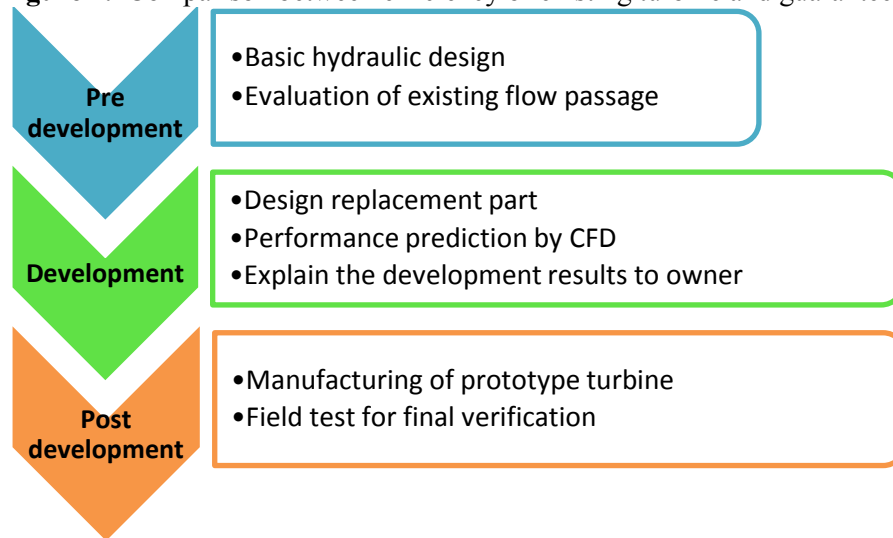
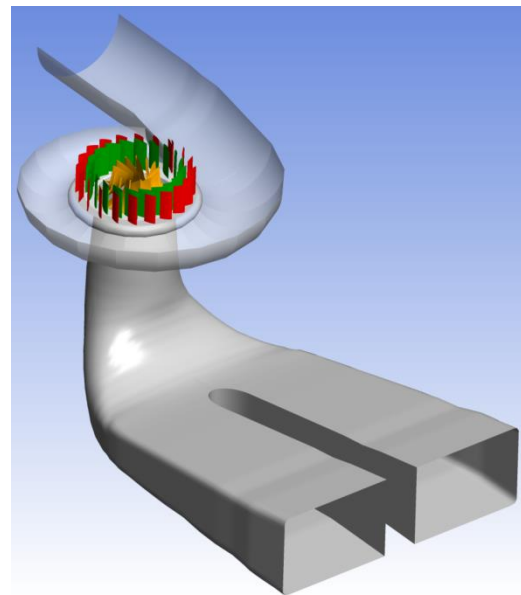


Figure 1. Comparison between efficiency of existing turbine and guaranteed value.**Figure 2.** Process flow of rehabilitation project.

3.1. Pre development stage

In pre development stage, in general, hydraulic loss of each component in the existing turbine was evaluated by using CFD analysis to provide the evidence for the goal of rehabilitation [2] [3] [4]. But, the dimension details of all components were unknown as mentioned before; therefore, hydraulic specification of existing power station was predicted by using already-known model testing result of Francis type turbine with similar specific speed and effective age.

The hydraulic loss of each component in Francis turbine with similar specific speed was evaluated by CFD to provide the goal of this project. CFD analysis was carried out by using the commercial turbulent flow simulation software “ANSYS CFX v17.0”. Computational model of CFD has a three main component as shown in figure 3, which consist of the spiral casing with 20 stay vane and 20 guide vane, runner and draft tube. The basic hydraulic performances are evaluated by steady state CFD and operating stabilities (ex. Pressure fluctuation) are evaluated by unsteady CFD.

**Figure 3.** CFD analysis model.

3.2. Development stage

In development stage, replaced components (i.e. spiral casing, stay vane, guide vane, runner and draft elbow) were design to fulfil the specification requirements as mentioned in section 2.

3.2.1. Design and optimization

(1) Spiral casing and Stay vane

The profiles of spiral casing and stay vane were optimized to reduce the hydraulic loss. The spiral casing was designed with due considerations to ensure the compatibility with decreasing the hydraulic loss and keeping the constant flow angle at the inlet of stay vane.

The stay vane profiles of old machine are often crude and were chosen more to be easy to manufacture. The stay vane of target power station also has a typical old type profiles, so that the stay vane profiles were modified in order to reduce their intrinsic losses as well as to better suite with the guide vane.

CFD analysis shows the effectiveness of modification of spiral casing and stay vane as shown in figure 4. The flow behaviour around the stay vane was improvement as well as estimated the losses reduction due to the modification as mentioned before.

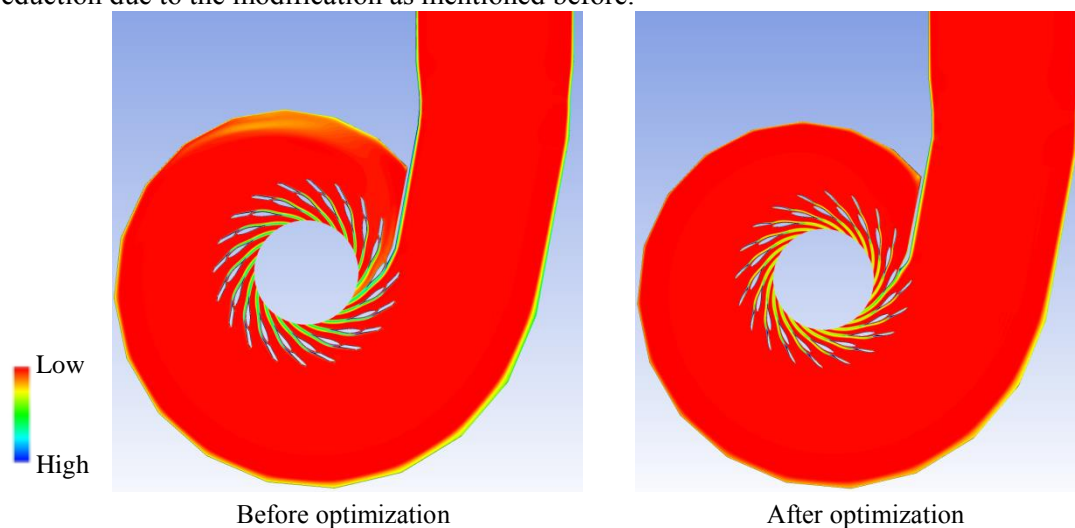


Figure 4. Hydraulic loss around spiral casing, stay vane and guide vane.

(2) Guide vane

The guide vane generates a high level hydraulic loss because they were operated in the wide band flow angle. The replacement of the existing guide vane to optimized one, generally leads to significant improvement of the turbine performance.

During the optimization, the results of CFD analysis show the interesting potential in guide vane replacement. Figure 5 shows the hydraulic loss comparison between old shape and new shape. The model efficiency at operating head was increased more than 0.5% by using the optimized guide vane profiles. The characteristics of torque acting on the optimized guide vane denoted the same tendency of old guide vane and the guide vane opening force was also same value, so that the specification of servomotor will not have to change.

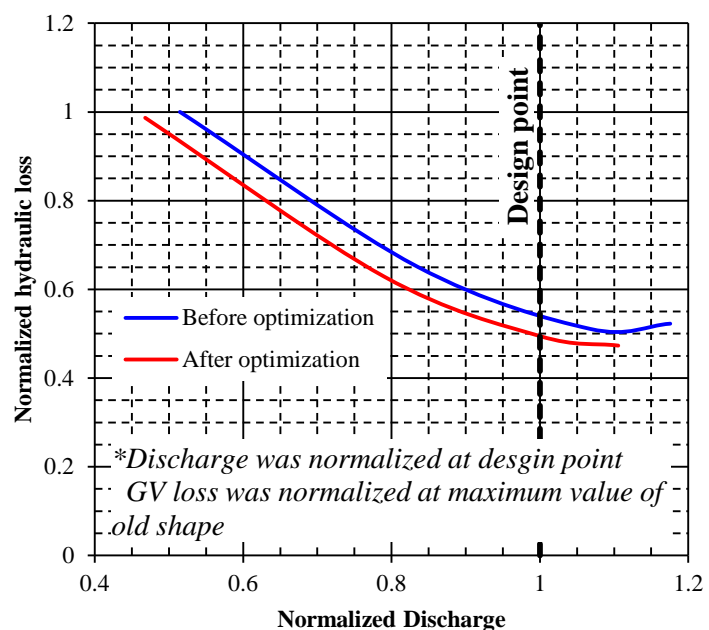


Figure 5. Hydraulic loss of guide vane.

(3) Runner

Even if all the hydraulic components are important and can badly affect the whole turbine performance by a poor design. The runner remains the key component to fulfil the guaranteed performance of the target power station.

Design and optimization of runner was also done by steady state CFD analysis within specified net head and discharge. On this optimizing phase, different CFD model was used so as to reduce the analysis time. The CFD model of runner optimizing phase was shown in figure 6. This CFD model consists of the 2 pitch stay vane, guide vane and 1 pitch Runner and draft tube. All components of this model were connected each other by GGI interface and have the periodic interface on the rotational direction. The inlet boundary condition of stay vane was obtained from the CFD results of optimum spiral casing and stay vane, and outlet boundary condition of the draft tube was opening condition.

On this optimizing phase, mainly increase the turbine efficiency and cavitation performance (σ_i). Figure 7 shows the turbine performance comparison between the old runner and optimized runner. The optimized runner can be increased the turbine performance.

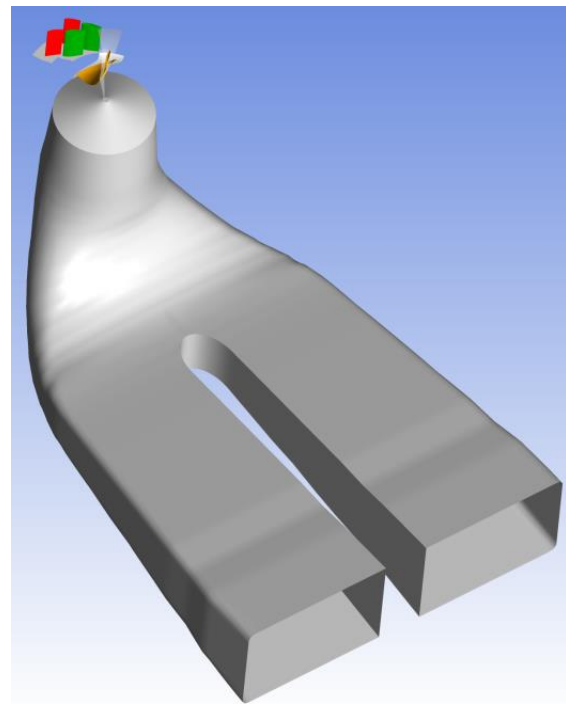


Figure 6. CFD analysis model for runner optimization.

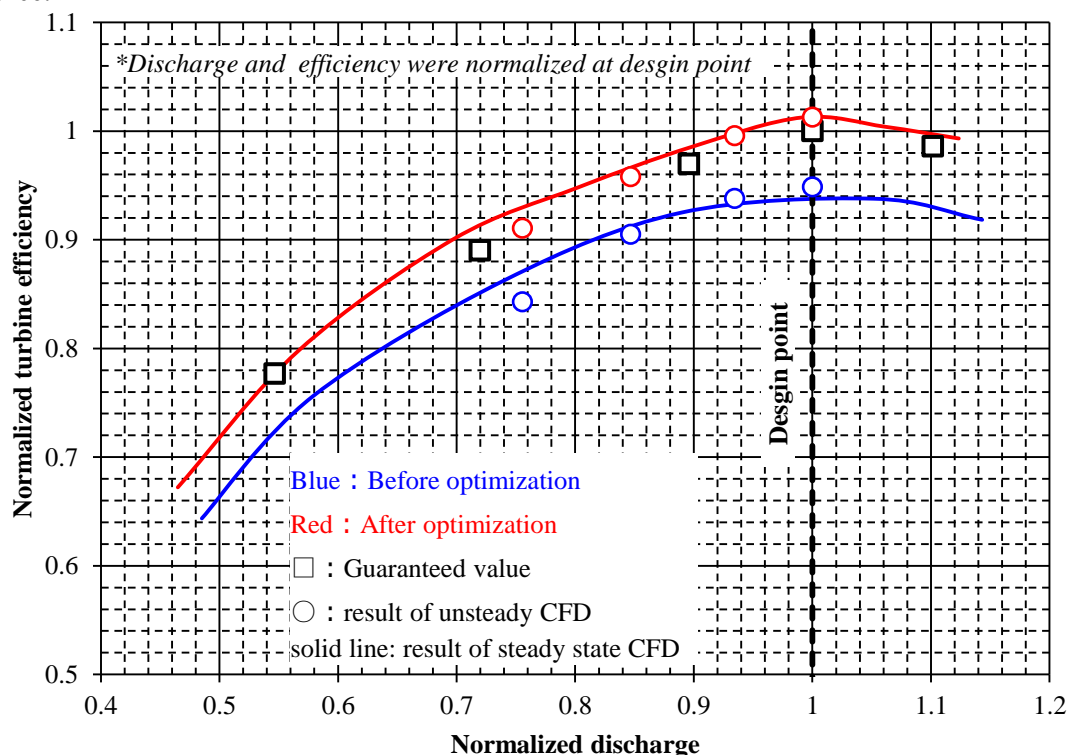


Figure 7. Calculation result of turbine optimization by steady flow analysis.

On the old runner surface, especially near inlet, has the low pressure area as shown in figure 8. The cavitation might occur at this low pressure area on the prototype, that is, the old runner has a poor cavitation performance on the all operating range.

The optimized runner, on the other hands, low pressure area near inlet was disappeared and the surface pressure decreases smoothly from the inlet to the outlet, that is, cavitation performance was improvement.

After obtaining the runner which can fulfil the specification requirement as described in Section 2, unsteady CFD analysis with full passage geometries from spiral casing to draft tube was performed for performance confirmation. The results of turbine efficiency are which obtained by unsteady CFD, show the almost same value of the steady state CFD as shown in Fig.7.

Another purpose of unsteady CFD analysis is to evaluate the operating stability. Figure 9 shows the result of pressure fluctuation at operating range. The optimized runner can decrease the pressure fluctuation compared with the old runner. Furthermore, that value shows almost same value of the experiment results of smaller specific speed Francis type turbine ($N_s \approx 270$ m-kW).

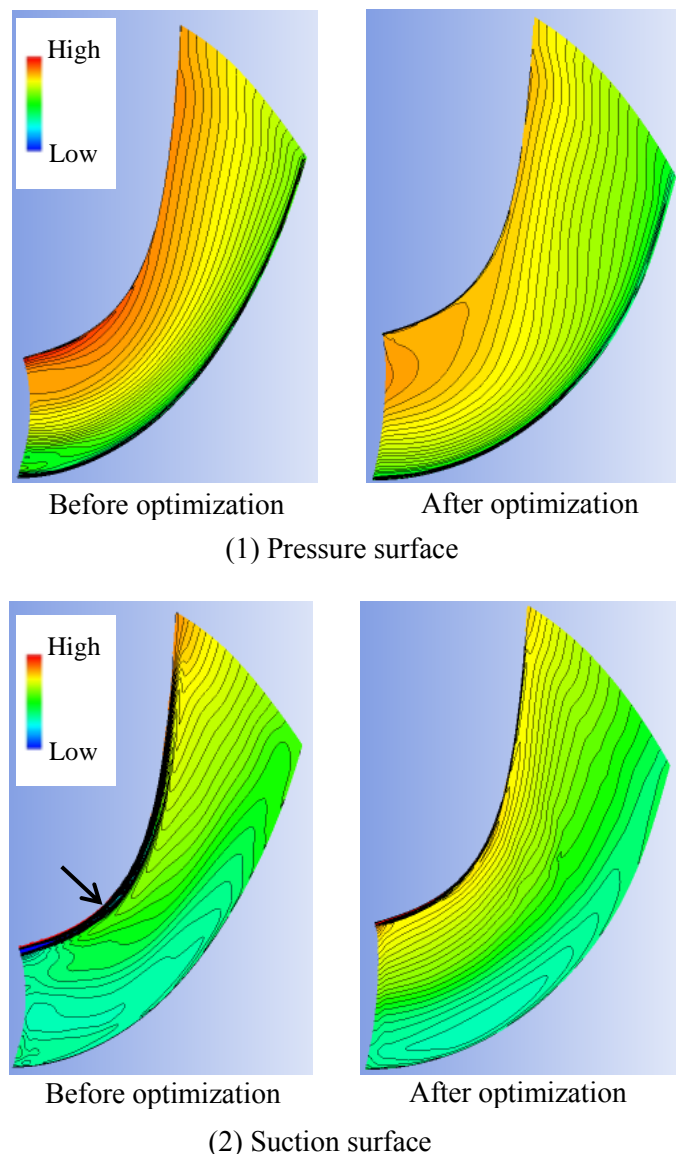
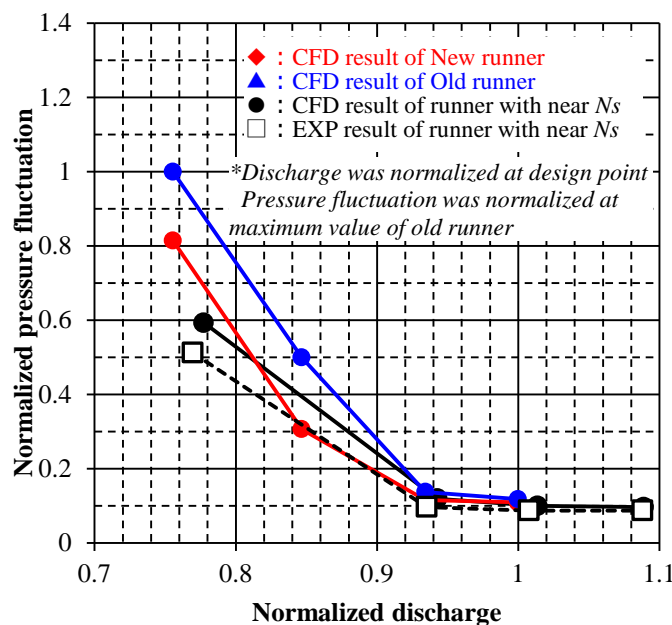


Figure 8. One example of pressure distribution on turbine surface (100% power).

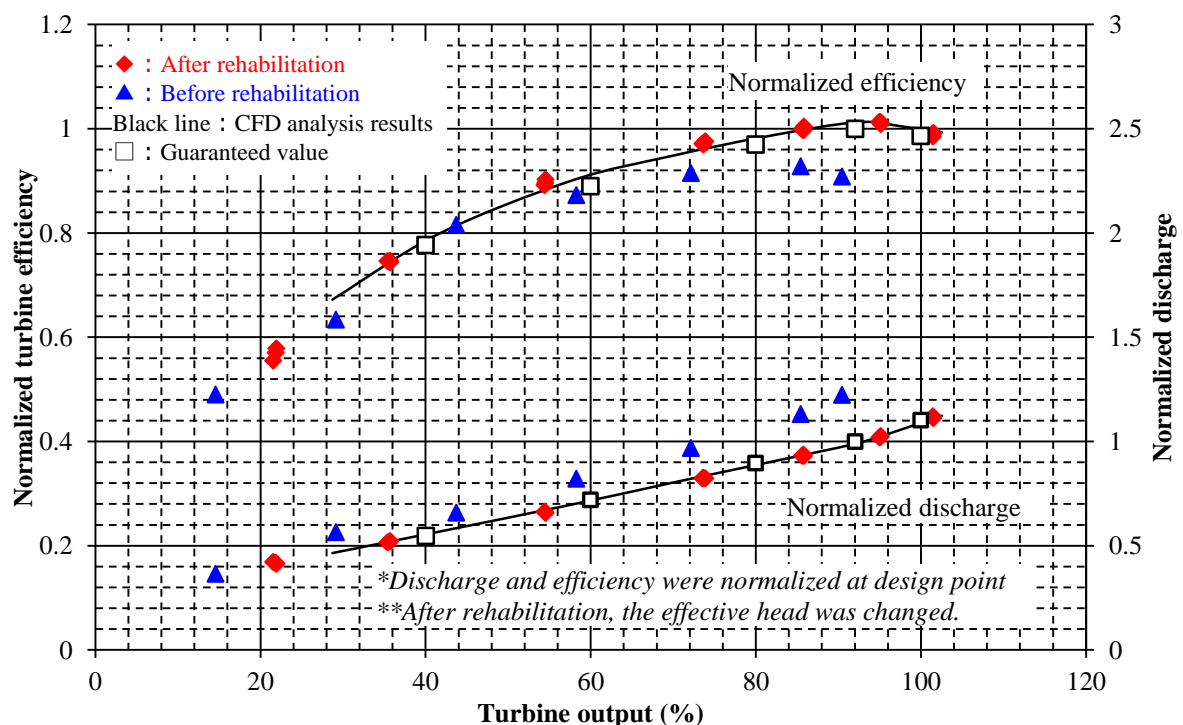
3.3. Post development stage

After the meeting to explain the development results to owner of power station, the prototype of power station was manufactured and installation on the site finished in the middle of year 2017. Figure 10 shows the installation of prototype turbine at site. The field tests were carried out in August of year 2017 to confirm the performance of new turbine. The results of turbine efficiency and discharge at net head obtained during field test for the existing and new turbine are compared relatively in figure 11, and it is evident that the new turbine has better performance compared with existing turbine over the whole operating range. Moreover, CFD results of the turbine efficiency are in good agreement with the result of field test. This result shows the evidence to support the validity of CFD evaluation method for turbine efficiency.

**Figure 9.** Calculation result of pressure fluctuation.**Figure 10.** Site installation of new turbine.

Besides that, the new turbine also operates with low noise compared with the existing turbine throughout the whole operating range. This is proven from the field test results as shown in figure 12, which shows the noise level for the new turbine drops by approximately 10% compared with the existing turbine.

After the field test, this power station is operated 24 hours per day. There is no trouble such as noise, vibration or decreasing the output. Furthermore, no sign of cavitation was observed in prototype runner surface.

**Figure 11.** Field test result of turbine performance.

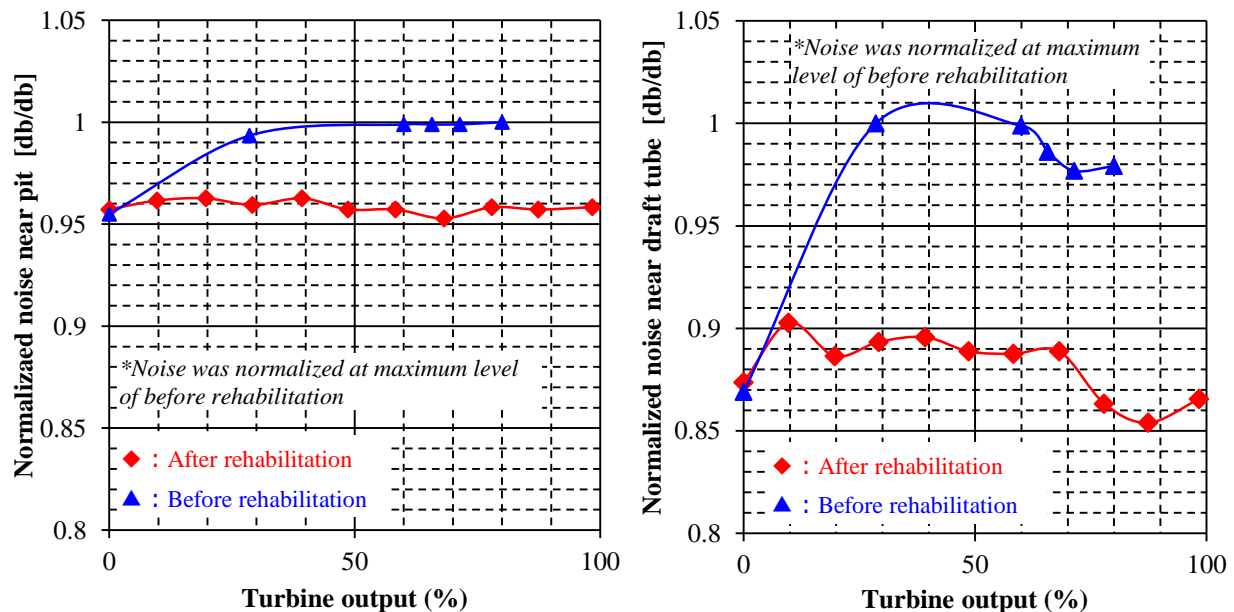


Figure 12. Comparisons of prototype turbine noise level.

4. Conclusion

This paper discussed about the CFD-based rehabilitation project. The strategy applied to overcome the challenges to improve the performance and verification of the calculated results was described. From this paper, the followings can be concluded.

- (1) The new runner was designed to be able to generate the more power, low noise and high operating stability through the whole operating range as compared with the existing turbine.
- (2) The new runner has the excellent cavitation performance.
- (3) The CFD analysis method was proven to be able to predict the turbine performance and operating stability with good accuracy by field test.

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