Analysis of the key hydraulic performances of pump-turbine with splitter blades

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ABSTRACT

Pressure fluctuations generated within the vaneless space of a pump-turbine are directly related to the ability of the unit to operate in a stable manner. Using the runner with splitter blades is a way to improve the stability of the unit. In this study, the model test results of pump-turbine runners in pumped-storage power plants in China are used to statistically analyze the efficiency and the amplitude of pressure fluctuations in the vaneless space of different units in several power plants since 2000. On this basis, combining the model and prototype test results before and after the modification of unit 4# of Heimifeng Pumped Storage Power Plant, the efficiency, amplitude and frequency of pressure fluctuation in the vaneless space of the conventional blade runner and the splitter blade runner are compared, and the advantages of the design of the splitter blade runner in reducing pressure fluctuation are given in a quantitative manner.

Keywords: Pump-turbine, splitter blade, statistical analysis, hydraulic efficiency, pressure fluctuation, vaneless space

1. INTRODUCTION

To achieve the goals of carbon peak and carbon neutrality, China is actively engaged in optimizing its energy structure and developing smart grids[1]. The installed capacities of wind energy, solar energy, and nuclear power are experiencing significant increases. As a means to ensure energy storage, pumped storage hydropower has witnessed unprecedented growth[2], with the deployment of pump-turbine units at a rate of several dozen units per year. In recent years, in newly commissioned and under-construction pumped storage plants, the use of pump-turbines with splitter blades has been on the rise. Studying and mastering their primary hydraulic performance under various operational working conditions will lay a solid foundation for the subsequent applications of these turbines in power plants, holding significant importance.

The splitter blades are widely applied in various types of turbomachine and have achieved a mature level of application in pumps and hydro turbines[3]. It demonstrates advantages such as the ability to improve efficiency[4-6], enhance flow capacity[4,7], increase resistance to cavitation[8,9], reduce pressure pulsations[10-12], and minimize vibration intensity[4,13,14]. The operational requirements of pump-turbines are more complex, and they have higher overall performance demands. Building upon research in the field of pumps and hydro turbines, investigations related to pump-turbines with splitter blade runners primarily focus on the influence of splitter blades configurations on flow conditions[15], efficiency characteristics, stability[16], rotor-stator interaction[17], and the impact of geometric parameters such as the number of long blades and short blades[18], the diameter of runners[19], and the length ratio of long blades and short blades to the pump-turbine's hydraulic performance[20,21].

Current literature reports mainly focus on the analysis and evaluation of the performance of pump-turbines with splitter blade runners for specific units[22-25]. This analysis is often based on model results or test data, which are compared with contractual guarantees and operational standards[26,27]. However, there is a lack of comparison of statistical data between the primary hydraulic performance of pump-turbines with splitter blade runners and conventional pump-turbines[28-30]. Additionally, the number of operational pumped storage power plants employing pump-turbines with splitter blade runners is relatively small, leading to limited research on the performance of splitter blade runners using field test data.

This paper analyzes the key hydraulic performance indicators of pump-turbines in pumped storage power plants in China over the past two decades from a statistical data perspective. This analysis objectively and accurately reflects the efficiency

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and pressure fluctuation levels of the runners with splitter blades across various head ranges. Drawing upon a combination of model experiments and test results, a comprehensive comparison is made between the primary performance of the runners with conventional blades and the runners with splitter blades in unit 4# of the Heimifeng pumped storage power plant, both before and after modification. This exemplifies the advantages of pump-turbines with splitter blade runners in terms of their primary hydraulic performance and offers guidance for the selection of unit modifications in existing power plants and the design of new power plant units.

2. STATISTICAL ANALYSIS OF THE CHARACTERISTICS OF PUMPED-STORAGE PROTOTYPE UNITS IN CHINA

In this study, model and prototype test data of a portion of pump-turbines with splitter blades in China in the last 20 years were selected to focus on the statistics and analysis of the efficiency characteristics and pressure fluctuation amplitude-frequency characteristics of the units. In order to better illustrate the results of the statistics and analysis, it is necessary to explain the legends of Figures 1-4. The dots in these figures are conventional blade runners and the triangles are splitter blade runners. Yellow color indicates power plants before 2000; green and red color indicates power plants in the stage of introducing and absorbing non-autonomously developed technology between 2000 and 2009 and power plants in the stage of gradually moving to Chinese independent research and development between 2010 and 2019, respectively. The blue color indicates the newly built power plants in the past three years.

2.1 Statistical analysis of efficiency characteristics

Figure 1 shows the distribution of efficiencies of some prototype pumped-storage power plant units in China in recent years. Where the data about the efficiency of the units are the results of conversion from model tests to prototypes. From Figure 1, it can be seen that there were fewer power plants before 2000; more power stations were constructed during 2010-2019; and after 2010, the storage power plants in China were mainly concentrated in the head section of 300 m and above. In the past three years, the newly built power plants are also concentrated in the head section of 300 m and above, and the proportion of the application of splitter blade runners has increased significantly.

Overall, in the statistical sample, the rated efficiency of hydraulic turbines is between 90% and 94%, the highest efficiency in the operating range is concentrated between 92% and 95%, and the weighted average efficiency is concentrated between 90% and 93%. The pumps have higher rated efficiencies than the turbines, ranging from 91.5% to 94.5%. Although the sample of splitter blade runners is small, it can be seen that their efficiency performance is at the average level in the middle head section of 300-500 m, where individual units have better than average efficiency performance; in the high head section of 600 m and above, the efficiency performance is significantly better than the average value.

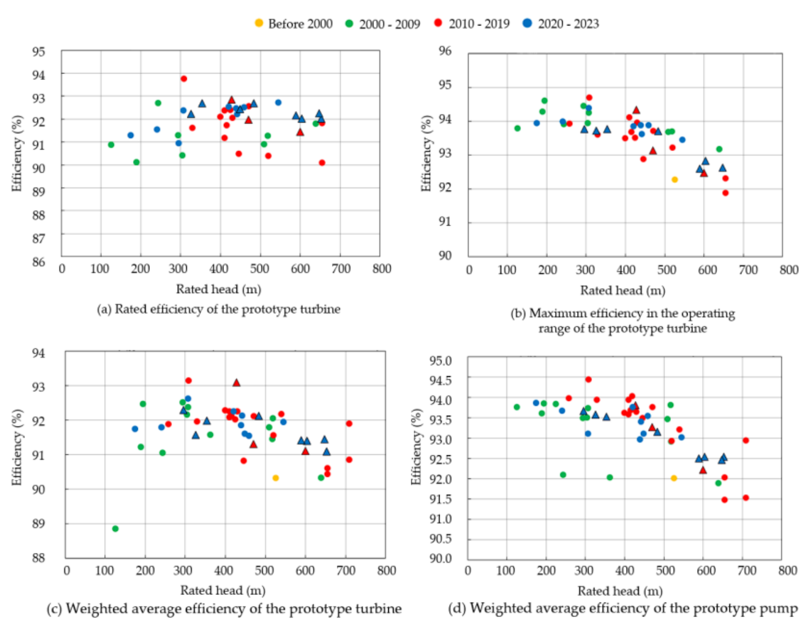
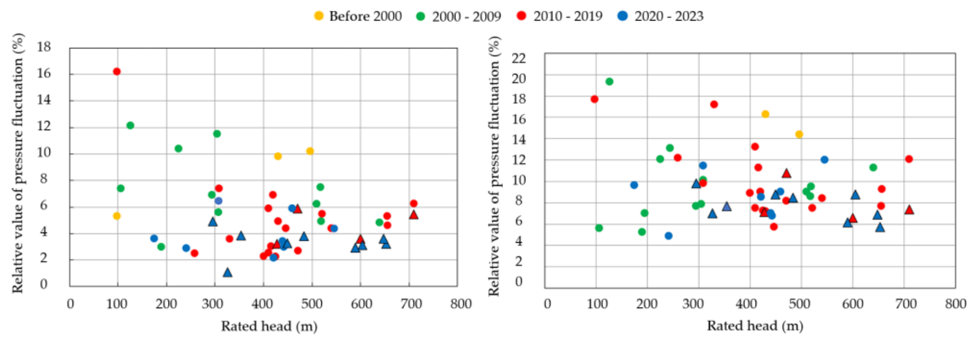


Figure 1. Statistics on efficiency characteristics.

2.2 Statistical analysis of pressure fluctuation amplitude-frequency characteristics

Pressure fluctuations in the vaneless space of a pump-turbine often have a large impact on the stability of the unit. This study focuses on statistically analyzing the pressure fluctuation in the vaneless space.

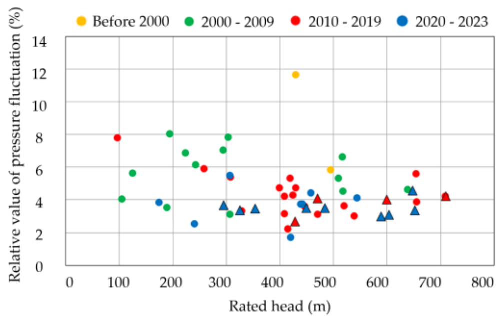
Figures 2 and 3 show the model test results of the relative amplitude of pressure fluctuation in the vaneless space of pumped-storage power plants in recent years in China.



(a) Pressure fluctuation at rated operating conditions in vaneless spaces of the turbine

(b) Pressure fluctuation at part load operating conditions in vaneless spaces of the turbine

Figure 2. Statistics of pressure fluctuation distribution in vaneless space of turbine mode.



Pressure fluctuation in operating range in vaneless spaces of the pump

Figure 3. Statistics of pressure fluctuation distribution in vaneless space of pump mode.

With the gradual improvement of the design level, the level of pressure fluctuation amplitude in the vaneless space gradually decreases, especially after 2020, the level of fluctuation has been substantially improved in both rated and part-load conditions. From 2010 to 2019, the relative amplitude of pressure fluctuation in the vaneless space of the turbine under the rated condition is basically located at less than 8%; from 2020 onwards, most of the results are less than 6%, with the splitter blade runners results mostly below 4%. The part load condition referred to in this study refers to the 50% load condition at the unit's rated head, and the final value selected is the maximum value of the relative value of pressure fluctuation, i.e., the most unfavorable case. Between 2010 and 2019, the results of the vast majority of the units lie below 14%, with more in the range of 6% to 10%; since 2020, the level of pressure fluctuation has further decreased, with all of them lying below 12% and more in the range of 6% to 9%, with units using splitter blade runners basically below 9%, with the lowest value reaching 5.75%.

The vaneless space pressure fluctuation in the operating range of pumps is overall better than that of turbine mode, with the relative value of pressure fluctuation in the range of 2% to 6% for the majority of units between 2010 and 2019; since 2020, the pulsation level has decreased to less than 5% except for some units, and basically less than 4% for splitter blade runners. It can be seen that the pressure fluctuation level in the vaneless space of the splitter blade runner is advantageous.

Figure 4 shows the overall level statistics of the amplitude of pressure fluctuation in the vaneless space of the pump-turbine.

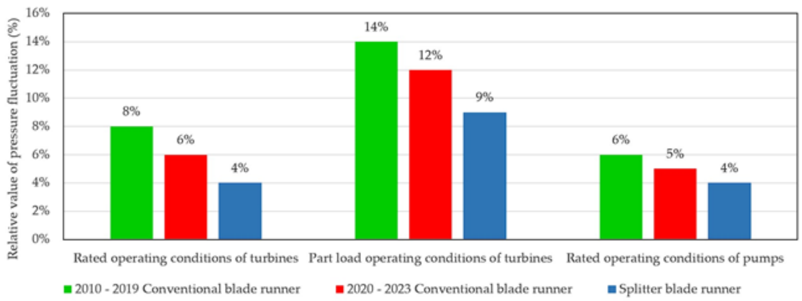


Figure 4. Statistics on the overall level distribution of pressure fluctuations in the vaneless space.

3. COMPARATIVE ANALYSIS OF THE PERFORMANCE CHARACTERISTICS OF HEIMIFENG UNIT 4# BEFORE AND AFTER MODIFICATION

Based on the statistical analysis of the data in the past 20 years, combined with the actual situation of the current pumped-storage power plants in China, we focus on selecting unit 4# of Heimifeng Pumped-Storage Power Plant as a typical case for analysis. This part synthesizes the model test and prototype measured data and analyzes the performance characteristics of the splitter blade runner.

Heimifeng Pumped Storage Power Plant is a typical unit for the introduction and absorption of non-autonomously developed energy storage technology in China after 2000, designed and manufactured by ALSTOM, France, with the number of blades and guide vanes of 9 and 20, respectively, and its characteristics represent the mainstream pumped-storage units in the same period. The acceptance test of the pump-turbine model was carried out in January 2007 at the TP3 test stand of the hydro-mechanical test laboratory of ALSTOM in Grenoble, France. After the commissioning and operation of the power plant, all 4 units had problems such as the turbine working in no-load and grid connection condition cannot reach the rated speed and fluctuates in the range of about ±10%, and the pressure extremes of the two units of the same hydraulic unit in the early stage of commissioning are different after losing part of the load at the same time. Therefore, starting in 2013, State Grid Xinyuan Company Ltd., Heimifeng Pumped Storage Company Ltd., design enterprises, research institutes, and Dongfang Electric Machinery Co., Ltd. jointly carried out the modification work of unit 4#.

In January 2019, the model acceptance test of the retrofitted unit 4# was conducted at the TP1 hydraulic test stand of the China Institute of Water Resources and Hydropower Research for acceptance. The retrofitted unit adopts splitter blade runners. Limited to the number of guide vanes and some major dimensions that cannot be changed, the Heimifeng unit 4# for the first time adopts a combination of 6 long blades, 6 short blades and 20 guide vanes under the existing conditions. Although it is different from the current mainstream combination of 5 long blades, 5 short blades and 16 guide vanes, as a modified pumped storage unit, the analysis and comparison of the main performance of Heimifeng unit 4# is of great significance in guiding the design and modification of the subsequent units, as well as the development of pumped storage technology.

3.1. Comparative analysis of efficiency characteristics

A comparison of the main efficiency characteristics of turbine mode and pump mode before and after the modification of Heimifeng unit 4# is shown in Table 1. The efficiency characteristics of the turbine mode have been reduced, and the efficiency of the pump mode has been improved. Since the modification of Heimifeng unit 4# is not primarily aimed at efficiency, the purpose of the modification can be achieved by ensuring that the efficiency level is not reduced.

Table 1. Comparison of efficiency characteristics before and after modification.

Efficiency characteristics	Pump mode		Turbine mode			
	Optimal efficiency	Weighted efficiency	Optimal efficiency	Highest efficiency in the operating range	Rated efficiency	Weighted efficiency
Before modification	93.65%	93.48%	95.16%	94.44%	91.29%	92.51%
After modification	94.01%	93.66%	94.46%	93.76%	90.94%	92.29%

3.2. Comparative analysis of pressure fluctuation model test results in the vaneless space

The results of the comparison of the relative amplitude of pressure fluctuation in the vaneless space of the turbine weighting points before and after the modification of the Heimifeng pump-turbine unit 4# are shown in Table 2 and Figure 5. Since the acceptance test only selected some working condition points for review and validation, the above charts and graphs use the results of the model's preliminary test. From the results, it can be seen that, except for the individual working condition points of high head (335 m) where the relative amplitude of pressure fluctuation in the vaneless space before and after the modification does not differ much, the amplitude of fluctuation in the rest of the weighted points is significantly reduced. Especially at the low head of 270 m, the relative amplitude is reduced by more than 3%. Close to the rated head (295 m) of 310 m, the magnitude of the reduction is also more obvious; in the high head of 335 m of 80% and 90% load conditions, the magnitude of the pressure fluctuation slightly increased, but the difference is not significant, less than 0.3%.

Overall, for the pressure fluctuation in the vaneless space of the Heimifeng unit 4# in turbine mode, the amplitude of fluctuation of the splitter blade runner is significantly lower than that of the conventional blade runner in the 50%~100% load of the medium and low heads and in the conditions of less than 70% load of the high head. The amplitude is comparable in the conditions of more than 70% load of the high head. The splitter blade runner has obvious advantages for improving the pressure fluctuation amplitude in the vaneless space.

Table 2. Comparison of the relative amplitude of pressure fluctuation in the vaneless space of the turbine weighting points.

Head	Load	50%	60%	70%	80%	90%	100%
H=270 m	Before modification	/	/	11.18%	10.49%	/	/
	After modification	/	/	7.46%	7.31%	/	/
	Reduction value	/	/	3.72%	3.18%	/	/
H=310 m	Before modification	9.20%	7.73%	6.25%	5.07%	4.23%	4.39%
	After modification	6.56%	6.40%	5.14%	3.98%	3.77%	3.81%
	Reduction value	2.64%	1.33%	1.11%	1.09%	0.46%	0.58%
H=335 m	Before modification	6.79%	5.41%	4.07%	3.09%	2.75%	2.40%
	After modification	3.90%	3.91%	3.80%	3.38%	2.93%	2.02%
	Reduction value	2.89%	1.50%	0.27%	-0.29%	-0.18%	0.38%

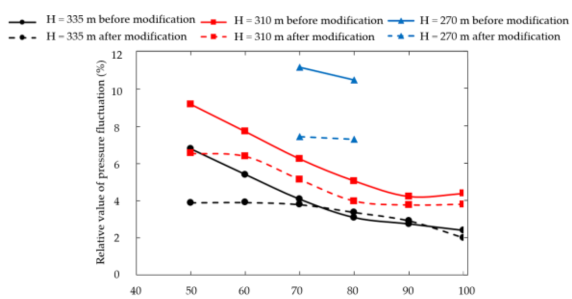


Figure 5. Comparison of pressure fluctuation amplitude before and after modification in the vaneless space of model turbine.

With the change in the number of blades, the dominant and other peak frequency amplitudes of the pressure fluctuation in the vaneless space also change. Taking the H=310 m, 50% load condition as an example, the comparison of the first three dominant frequencies amplitudes is shown in Table 3. Before the modification, the dominant frequency has $9f_n$ of blade overcurrent frequency and its 2x and 3x frequencies, and the corresponding frequency amplitudes are 1.59%, 0.5%, and 0.45%, respectively. After the modification, the dominant frequency is changed to $6f_n$ and $12f_n$, which are directly related to the number of blades, and the amplitude of the first dominant frequency is reduced to 1.39%. At the same time, the frequency amplitudes of the first three dominant frequencies are more uniform than before the modification. It can be seen that the dominant frequency of pressure fluctuation in the vaneless space is changed to the blade overcurrent frequency related to the number of long and short blades, the amplitude of the first dominant frequency is reduced, and the amplitude of the first three dominant frequency is relatively more equal than that of the conventional blade runner, and the total fluctuation energy is distributed by the fluctuation components of more frequency components.

Table 3. Comparison of the first three dominant frequencies and their corresponding relative amplitudes in vaneless space for the model turbine at H=310 m, 100% Load.

	f_1/f_n	f_2/f_n	f_3/f_n	A_1/H	A_2/H	A_3/H
Before modification	9	18	27	1.59%	0.50%	0.45%
After modification	12	6	6	1.39%	1.12%	0.93%

The comparison of the relative amplitude of pressure fluctuation in the normal operation condition and the best operation point of the vaneless space in pump mode before and after the modification is shown in Table 4 and Figure 6, and the data are adapted from the results of the preliminary model test. It can be seen that after the modification of the pump operating range broadened, the intersection of the two curves flow rate of about 81.7 m^3/s, corresponding to the head of about 321 m. In the higher than 321 m head operation, the pressure fluctuation amplitude in the vaneless space around the splitter runner was significantly reduced. In the lower than 321 m head operation, although the pressure fluctuation amplitude of the conventional vane runner increased, the increase was not large.

Table 4. Comparison of pressure fluctuation in the vaneless space under model pump conditions.

	Normal conditions	**Optimal condition**
Before modification	6.76 %	1.90 %
After modification	4.50 %	2.70 %

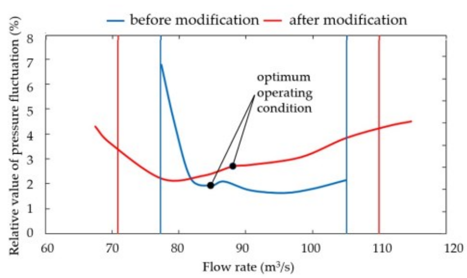


Figure 6. Comparison of pressure fluctuation amplitude in vaneless space of model pump before and after modification.

In general, after modification, the pressure fluctuation in the vaneless space of the Heimifeng unit 4# in pump mode fluctuates more gently in all operating ranges, reflecting a smoother flow state than before, especially improving the pressure fluctuation in the range of high head and small flow conditions.

The dominant frequency of pressure fluctuation in the vaneless space of the pump has also been changed. For example, the dominant frequency has been changed from the original blade overcurrent frequency of $9f_n$ and its 3 times frequency to the blade overcurrent frequency of $12f_n$ and its 2 times frequency of the splitter blade runner. The comparison of the first three dominant frequencies amplitude is shown in Table 5. The amplitude of the dominant frequency before the modification is 0.89%, 0.47%, and 0.19%, and is reduced to 0.37%, 0.21%, and 0.17%, respectively, after modification. As in the case of the turbine mode, the amplitude of the dominant frequency tends to be more uniform.

Table 5. Comparison of the first three dominant frequencies and their corresponding relative amplitudes in vaneless space for the model pump at Q=77.2 m^3/s.

	f_1/f_n	f_2/f_n	f_3/f_n	A_1/H	A_2/H	A_3/H
Before modification	0.1	9	27	0.89%	0.47%	0.19%
After modification	12	24	44	0.37%	0.21%	0.17%

3.3. Comparative analysis of pressure fluctuation prototype results in the vaneless space

The comparison of the relative amplitude of pressure fluctuation in the vaneless space before and after the modification of the prototype unit of Heimifeng pump-turbine unit 4# within the range of 301-306 m is shown in Figure 7, and the amplitude of fluctuation in the unit after modification is significantly reduced in the 50%-100% load. The comparison of the first dominant frequency at 50% and 100% load conditions is shown in Table 6. The dominant frequency of pressure fluctuation in the vaneless space is changed from $9f_n$ to $12f_n$, and the amplitude of the first dominant frequency is significantly reduced.

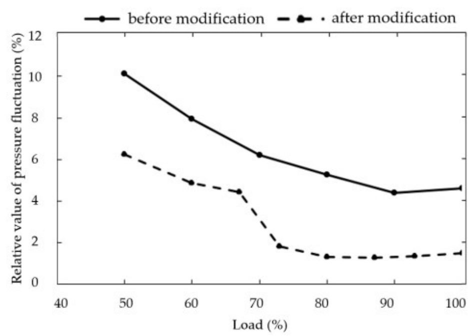


Figure 7. Comparison of pressure fluctuation amplitude in vaneless space of prototype turbine before and after modification.

Table 6. Comparison of dominant frequency in vaneless space of prototype turbine before and after modification.

Load		f_1/f_n	A_1/H
50%	Before modification	9	3.08%
	After modification	0.375	1.58%
100%	Before modification	9	1.67%
	After modification	12	0.69%

It can be seen that, both from the model results and the prototype results, the splitter blade runners of the Heimifeng unit 4# have a significant reduction in the amplitude of pressure fluctuation in the vaneless space.

4. DISCUSSION AND CONCLUSIONS

This study draws the following conclusions through the statistical analysis of the data on the efficiency characteristics of the pump-turbine and the pressure fluctuation characteristics in the vaneless spaces of the splitter blade runner and the conventional blade runner, as well as the comparison of the results of the prototype tests and model tests of a typical storage power plant unit:

(1) The efficiency performance of the splitter blade runners is at an average level in the middle head of 300-500 m, where the efficiency performance of some of them is better than the average. However, in the high head of 600 m and above, the efficiency performance of the splitter blade runners is significantly better than the average level.

(2) For splitter blade runner units and conventional blade units of similar size in the same head section, the pressure fluctuation level in the vaneless space is usually lower in the former. This indicates that the design of splitter blades makes the pressure fluctuation performance advantageous.

(3) The unit 4# before and after the retrofitting of the Heimifeng Storage Power Plant is analyzed as a typical case. The results show that after retrofitting the runner into the design with splitter blades, the efficiency in the pump condition is improved from the efficiency, but the efficiency in the turbine condition is reduced. Overall, the efficiency level of the unit did not decrease significantly. No matter the model test results or the prototype test results, the pressure fluctuation amplitude in the vaneless space of the turbine and the pump has been significantly reduced, the dominant frequency has been significantly changed, which is directly related to the number of splitter blades.

Since the number of splitter pump-turbine units that have been put into operation is still relatively small, and there are differences in the main hydraulic parameters of the units that have been put into operation, such as head, capacity, rotation speed, and combinations of the number of blades and the number of guide vanes, etc., there is still room for further research on the performances of the pump-turbines with splitter blades.

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