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Hydrodynamic Design of Thrust Ring Pump for Large Hydro Turbine Generator Units

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Abstract

Thrust-ring-pump is a kind of extreme-low specific speed centrifugal pump with special structure as numerous restrictions from thrust bearing and operation conditions of hydro-generator units. Because the oil circulatory and cooling system with thrust-ring-pump has a lot of advantages in maintenance and compactness in structure, it has widely been used in large and medium-sized hydro-generator units. Since the diameter and the speed of the thrust ring is limited by the generator set, the matching relationship between the flow passage inside the thrust ring (equivalent to impeller) and oil bath (equivalent to volute) has great influence on hydrodynamic performance of thrust-ring-pump. On another hand, the head and flow rate are varying with the operation conditions of hydro-generator units and the oil circulatory and cooling system. As so far, the empirical calculation method is employed during the actual engineering design, in order to guarantee the operating performance of the oil circulatory and cooling system with thrust-ring-pump at different conditions, a collaborative hydrodynamic design and optimization is purposed in this paper. Firstly, the head and flow rate at different conditions are decided by 1D flow numerical simulation of the oil circulatory and cooling system. Secondly, the flow passages of thrust-ring-pump are empirically designed under the restrictions of diameter and the speed of the thrust ring according to the head and flow rate from the simulation. Thirdly, the flow passage geometry matching optimization between thrust ring and oil bath is implemented by means of 3D flow simulation and performance prediction. Then, the pumps and the oil circulatory and cooling system are collaborative hydrodynamic optimized with predicted head-flow rate curve and the efficiency-flow rate curve of thrust-ring-pump. The presented methodology has been adopted by DFEM in design process of thrust-ring-pump and it shown can effectively improve the performance of whole system.

Keywords: Thrust-ring-pump, Hydrodynamic design, Thrust bearing, Lubricating and cooling system, Hydro turbine generator, Low specific speed centrifugal pump

1. Introduction

Thrust bearing is one of the most important components for hydro turbine-generator units, and it’s lubricating and cooling systems is essential for thrust bearing and even for keeping normal operation of the whole hydraulic turbine-generator. Because the oil circulating and cooling system with thrust-ring(or cone) -pump has a lot of advantages in maintenance and compactness in structure[1], it has become a trend to use this kind of self-pumped thrust ring pump to increase oil circulating pressure for lubricating and cooling systems of large and medium-sized hydro-generator in recent years[2-5].

Thrust-ring-pump obtains similar function of centrifugal pump with several holes (similar to impeller passage) drilled inside the thrust ring or thrust cone and the oil bath (equivalent to volute) installed at outer edge of the thrust ring or thrust cone. The speed of thrust-ring-pump is determined by the rotating speed of hydraulic turbine, and the dimension and structure of the thrust ring or thrust cone are limited by the structure of the generator. The holes pattern should be selected to ensure convenient in manufacturing, and it

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also must take into account that the influence from geometries and number of the hole on strength of thrust ring or thrust cone. However, the layout of hole pattern and number of holes inside the thrust ring or thrust cone, and the shape, area, outlet pipe diameter of oil bath and other geometric parameters have great influence on hydrodynamic performance of thrust-ring-pump. In theory, although thrust-ring-pump is a kind of centrifugal pump which has very special structure with numerous restrictions, the traditional design theory and method for centrifugal pump aren't fully applicable for this kind of extreme-low specific speed centrifugal pump. As so far, the hole inside the thrust ring or thrust cone is designed in the radial and backward direction, and the "head-discharge" curve of thrust-ring-pump is assumed as a parabola curve to approximately calculated the pump's head. Meanwhile , the oil bath is mainly been taken as a device to collect oil from outlet of the thrust ring holes and transport oil to the outlet of the lubricating and cooling pipe and its hydrodynamic performance isn't much been considered in actual engineering. This design methodology often leads to poor hydrodynamic performance for thrust-ring-pump [6-9].

In this paper, to the optimize the layout and number of holes and geometric parameters such as hole's shape, area, outlet pipe diameter of oil bath in hydrodynamic design of thrust-ring-pump, the influence from geometric parameters on hydrodynamic performance of thrust-ring-pump has been calculated and analysed under the constraint condition of manufacture and strength of thrust ring or thrust cone. The feasibility of the hydrodynamic performance prediction method for thrust-ring-pump by means of multi-condition numerical simulation has been verified by combining a test model of thrust-ring-pump for a large hydroelectric units thrust bearings. Grouping the different geometric parameters, the influence from flow passages geometric parameters on hydrodynamic performance of thrust-ring-pump can be analysed and predicted by the verified performance prediction method, and the influence from the key dimensions and the shape of flow passage on the pump have more deeply analyses. By this way, a performance prediction and optimization design method suitable for the flow passages of thrust-ring-pump has been explored, and it has been provided a theoretical foundation and effective technical approaches for optimization design of thrust-ring-pump and lubricating and cooling systems of the thrust bearings.

2. Numerical Simulation for Characteristics of Lubricating Cooling Systems and Determination of Design Parameters of Thrust-Ring-Pump

2.1 Lubricating and cooling systems for thrust bearings with thrust-ring-pump

Because the thrust load and the cooling discharge for a large hydro turbine generator is very heavy, the internal structure of thrust bearing can be greatly simplified by applying external circulation cooling system, and which has the advantage of disassembling thrust ring without disassembling the oil cooler, easy in maintaining thrust bearing and oil cooler, and repairing single oil cooler without influencing the use of other coolers [1]. In recent years, it has widely applied thrust-ring-pump to replace the additional pump located outside the lubrication oil reservoir in the external circulation cooling system for a large and medium-sized hydro turbine generator if the pressure can be increased more than 0.1Mpa by the way of self-pumping [6]. The discharge and pressure of circulating oil for thrust bearing circulating and cooling systems self-pumped by the thrust-ring-pump should be matched with pipe characteristic of lubricating and cooling systems. In the thrust-ring-pump design, firstly design parameters of thrust-ring-pump should be determined with numerical simulation of pipe characteristic on the basis of the layout of lubricating and cooling systems, or by adjusting the pipe characteristic obtained from numerical simulation to meet the requirements of operation parameters of thrust-ring-pump in actual engineering. Figure 1 shows the lubricating and cooling pipe system which includes four coolers of test-bed for verifying performance of the thrust-ring-pump.

Fig.1. The lubricating and cooling pipe systems of test-bed

2.2 Lubricating and cooling systems for thrust bearings with thrust-ring-pump

The self-pumped oil circulating and cooling system consists of a thrust-ring-pump, several oil coolers, valves, bends, junctions, pipes and so on. The layout and installation elevation of oil coolers, valves and pipes are different for different hydropower stations, and the pressure provided by thrust-ring-pump is also different. During the design of thrust-ring-pump, as the restriction of the size of thrust bearing and the speed of unit, if parameters of the pump can't be satisfied after calculation, you also can adjust the loss characteristic of components in the oil circulating and cooling system to meet the requirements of the thrust-ring-pump, so it is very important to accurately numerical simulate and optimize the pipe characteristics of lubricating and cooling systems. The one-dimensional hydrodynamic simulation for the oil circulating and cooling system of thrust-ring-pump test-rig has been conducted with Flowmaster® software, and figure 2 shows the model of the system in Flowmaster® software. In order to verify the accuracy of the numerical simulation result, the pipe characteristic tests of the oil circulating and cooling system of thrust-ring-pump test-rig has been conducted for systems with one, two, three oil coolers respectively at DFEM (Dongfang Electric Machinery Co. Ltd.). The simulation medium is turbine oil L-TSA46 with the density of 880 kg/m3 and the dynamic viscosity of 0.00089 kg/(m·s).

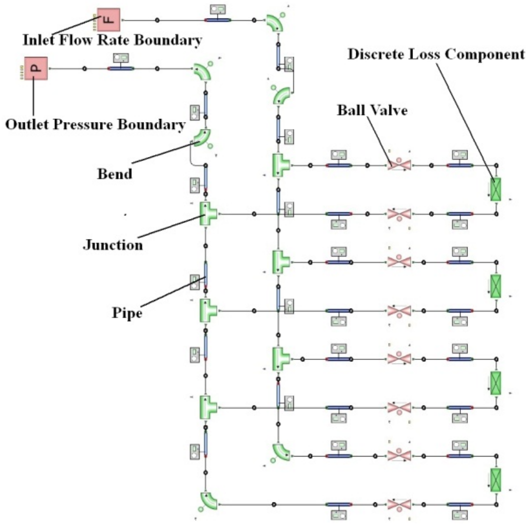


Fig.2. The simulation model of the cooling system in Flowmaster®

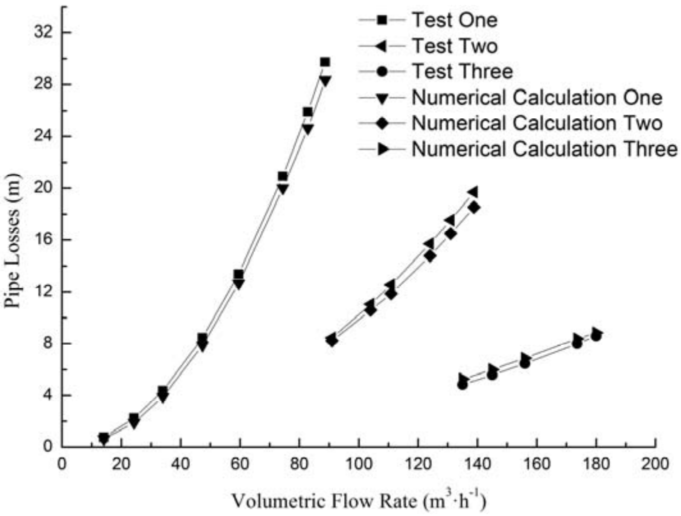


Fig.3. The results comparison between the test the data and simulation data obtained with one, two, three oil coolers respectively

Figure 3 shows the results obtained from both of the test and simulation. The numerical simulation results match the test results quite well.

2.3 Determination of hydrodynamic parameters for thrust-ring-pump

The head of thrust-ring-pump is determined by hydraulic losses in pipe lines of the oil circulating and cooling system and losses in thrust bearing. The flow rate of lubricating oil for thrust bearing is 124 m^3/h, which is the design flow rate for thrust-ring-pump, and the flow losses with the flow rate of 124 m^3/h in thrust bearing is 3.9 m. According to the figure 3, the pipe losses of the oil circulating and cooling system operating with two oil cooler is 15.7 m. So the head of thrust-ring-pump should be higher than19.6 m, set up 20 m. The speed of thrust-ring-pump is 225 r/min which is determined by the generator.

3. Hole Pattern inside Thrust Ring and Influence on Hydrodynamic Performance of Thrust-Ring-Pump

The structure and size of thrust bearing have been determined during the design of the hydro turbine-generator. The inner and outer diameter of the thrust ring is Φ1040mm and Φ2139mm respectively. According to the requirement for hydrodynamic parameters, the preliminary flow passages of the thrust-ring-pump (hereafter called scheme A) has been designed by means of the basic theory for centrifugal pump. This scheme has the following features: the holes inside thrust ring are radial straight holes with the diameter of Φ40 mm and the number of 8, and the oil bath has the base circle diameter of Φ2296 mm with the inlet width of 65 mm and total outlet area of 24531 mm2. The cross-sectional shape of oil bath is rectangular, with exterior lines of logarithmic spiral, and eight outlets is arranged evenly at circumferential direction. The 3D model of flow passages of thrust-ring-pump is shown in figure 5 (a).

3.1 Hole patterns inside thrust ring

In order to optimize the design of the hole patterns inside thrust ring, on the basis of the preliminary design of radial straight hole patterns (scheme A), taking account to the limitations of structural strength and manufacturing, another 5 kinds of hole patterns were designed for the above-mentioned thrust ring. In the design process, the number and the cross-sectional area of hole keep same respectively. . The table 1 lists the different parameters of the 6 schemes (labelled as A, B, C, D, E, F).

Tab.1. The feature of 6 schemes

Scheme	Hole central line	The sectional shape of holes	Passage features
A	radial line	Circular	All holes are radial straight hole
B	Inclined line	Circular	Drilling straight holes on the thrust ring, the most small Outlet angle is 61°
C	Multi-line (one outlet)	Circular	Outlet angle is 61°, inlet angle is 90°

D	Multi-line (two outlet)	Circular	Outlet angle of inclined hole is 61°, another hole is radial straight hole
Scheme	Hole central line	The sectional shape of holes	Passage features
E	Arc -line (outlet angle of 61°)	Square	Outlet angle is 61°, inlet angle is 90°
F	Arc -line (outlet angle of 20°)	Square	Outlet angle is 20°, inlet angle is 90°

3.2 3D models of six scheme's thrust-ring-pump

The flow passage of thrust-ring-pump is shown in figure 4. The definition of thrust-ring-pump geometry covers inlet, mirror plate holes, oil tank, and outlet pipes.

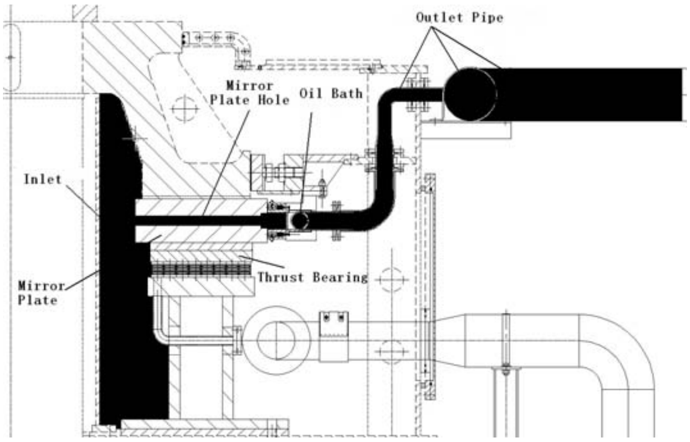
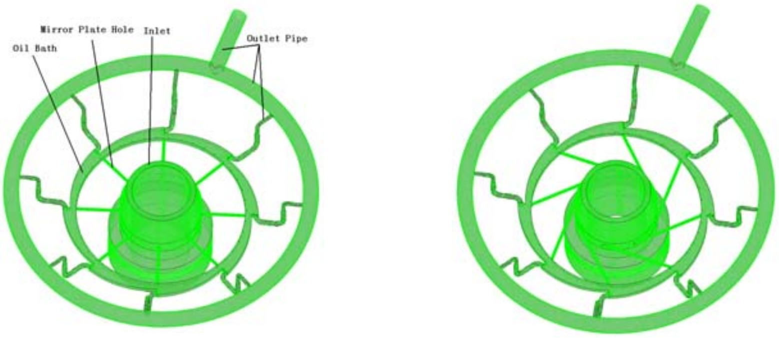


Fig.4. The flow passages of thrust-ring-pump

Firstly, the flow passage's three-dimensional model of every part was built with Unigraphics NX® software. Then, the grid of every part was generated with ICEM-CFD® software, and the mixed grid with tetrahedron and hexahedron was applied to all parts. Figure 5 shows the 3D flow passage models and grid of 6 schemes.



(a) scheme A

(b) scheme B

(c) scheme C

(d) scheme D

(e) scheme E (f) scheme F

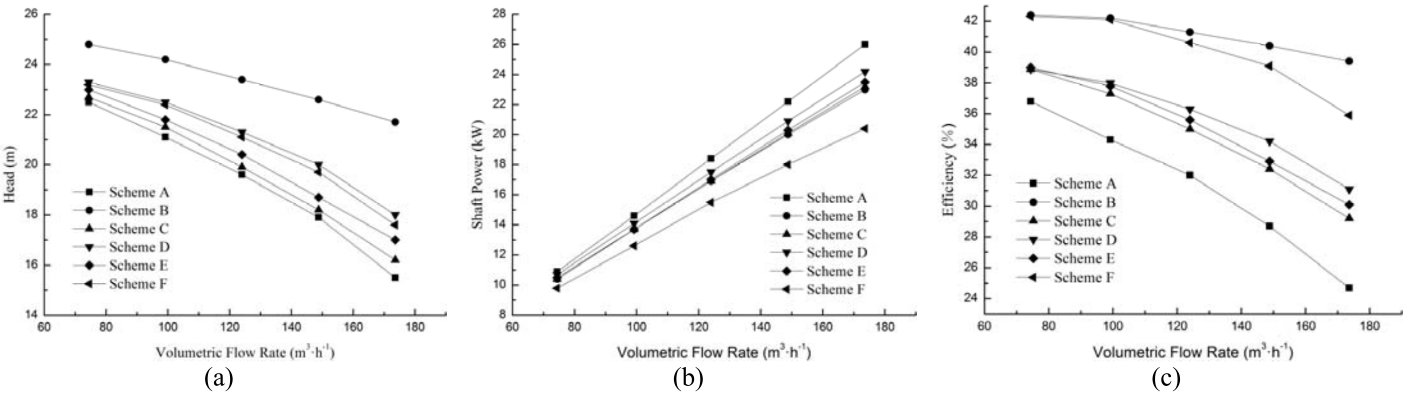
Fig.5. Three-dimensional models of thrust-ring-pumps flow passage with different holes pattern.

3.3 Numerical simulation method and multi-conditions numerical simulation

The numerical simulation was conducted by ANSYS/ CFX® software, which was applied to solve the Navier-Stokes equations, and the RNG k-Epsilon turbulence model. The boundary conditions are as follows: (a) the relative static pressure was setup at inlet, (b) mass flow rate was setup at outlet, (c) no-slip wall and smooth wall was assumed at wall, (d) scalable wall functions was used to deal with the near wall flow, and (e) “Frozen-rotor” model was applied to deal with interference between inlet and mirror plate hole, mirror plate hole and oil tank. The working medium of the thrust-ring-pump is turbine oil L-TSA46. The working conditions are simulated at flow rate of 74.4, 99.2, 124, 148.8, and 173.6m^3/h respectively.

3.4 Hydrodynamic performance analysis for the six scheme’s thrust-ring-pump

On the basis of numerical simulation, the external characteristic of the six schemes were predicted and shown in figure 6. The figure 6(a) shows that the head curves of six schemes are ordered from high to low as: B>D>F>E>C>A, While the head of scheme A is greatly higher than the others. From the figure 6(b), it is noticed that the shaft power curves of six schemes are ordered from high to low as: A>D>E>C>B>F. The figure 6(c) shows that the efficiency of scheme B is the highest, and the efficiency of scheme A is the lowest. The efficiency curves of six schemes are ordered from high to low as: B>F>D>E>C>A.



(a) (b) (c)

Fig.6. Performance curves of thrust-ring-pumps with different hole patterns

In order to further analyze the different passage’s influence on hydrodynamic performance of the thrust-ring-pumps, the thrust-ring-pump is divided into thrust ring and oil bath from viewpoint of energy conversion. The efficiency of thrust ring and oil bath is shown respectively in figure 6 and 7. The efficiency is defined as the ratio of output energy and input energy of thrust ring or oil bath. Figure 7 shows that the efficiency vary with discharge of thrust ring, and the efficiency curves of six schemes are ordered from high to low as : scheme B>A>E>C>D>F, while the efficiency curves of scheme B is much higher than others. Figure 8 shows that the efficiency vary with discharge of oil bath, and it is noticed that the efficiency curves of six schemes are ordered from high to low as: F>B>C>E>D>A. Each efficiency curve of oil bath has great difference in the variation trend. The efficiency of scheme F and B increases gradually along the increases of the flow-rate, and the efficiency curves of scheme C, E and D are more flat along the increases of the flow-rate, while the efficiency of scheme A decreases gradually along the increases of the flow rate.

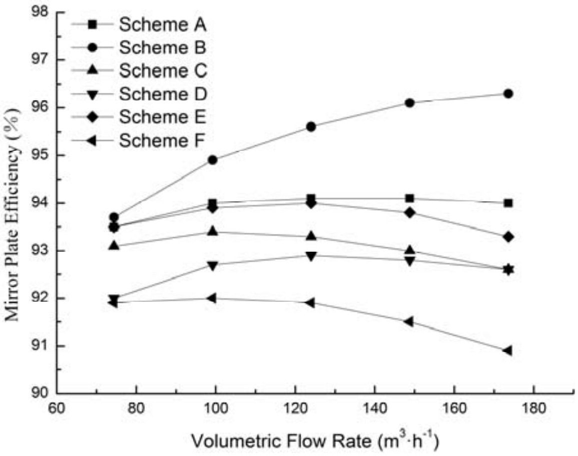


Fig.7. Efficiency curves of thrust ring

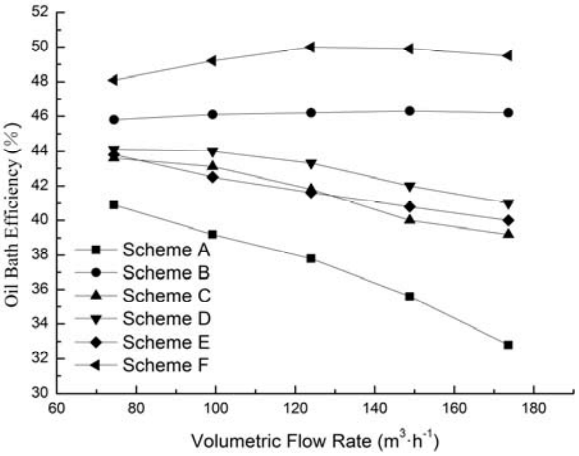


Fig.8. Efficiency curves of oil bath

The above analysis shows that outlet angle and inlet angle have great influence on the performance of thrust-ring-pump. If the structure allows, inlet angle with small incidence and small outlet angle should be applied in the design process of mirror plate hole.

4. Influence of Geometrical Parameters of Oil Bath on Thrust-Ring-Pump's Performance

As mentioned above, the performance of oil bath has not much been considered in actual engineering design, while it is mainly been taken as a device to collect oil from the outlet of thrust ring holes and transport it to lubricating and cooling pipes. From the above analysis, it should be noted that the oil bath is equivalent to volute of ordinary centrifugal pump, so the holes pattern inside thrust ring must match with flow passages of oil bath as the geometrical parameters of oil bath have great influence on thrust-ring-pump's performance. In another words, Oil bath is one of the most important parts of thrust-ring-pump, its flow passage must match with the holes pattern inside thrust ring in design. The influence from cross-sectional shape and outlet area of oil bath on thrust-ring-pump's performance have been below estimated by means of flow numerical simulation and analyzed in the followings.

4.1 Cross-sectional shape of oil bath

On the basis of the original oil bath (scheme A)with rectangular (RET)cross section, additional two kinds of oil bathes with trapezoidal (TRA) and circular (CIR) cross-sectional were designed under the same area. The oil bathes were designed with the law of constant velocity in all cross sections over the circumference, except cross-sectional shape, other geometrical parameters of oil bath are in accordance with that of thrust-ring-pumps with different hole patterns inside the thrust ring. Three kinds of cross-sectional shape are shown in figure 9. Combining 3 kinds of cross-sectional shape oil bathes with 6 kinds of hole patterns inside the thrust ring, we can generate 18 thrust-ring-pump's flow passage models as listed in Table 2.

Tab.2. Combination of flow passage models

Model No.	1	2	3	4	5	6	7	8	9
hole pattern	A	A	A	B	B	B	C	C	C
Oil bath shape	RET	TRA	CIR	RET	TRA	CIR	RET	TRA	CIR
Model No.	10	11	12	13	14	15	16	17	18
hole pattern	D	D	D	E	E	E	F	F	F
Oil bath shape	RET	TRA	CIR	RET	TRA	CIR	RET	TRA	CIR

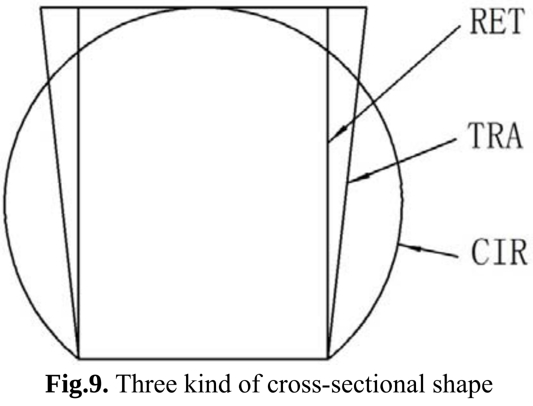
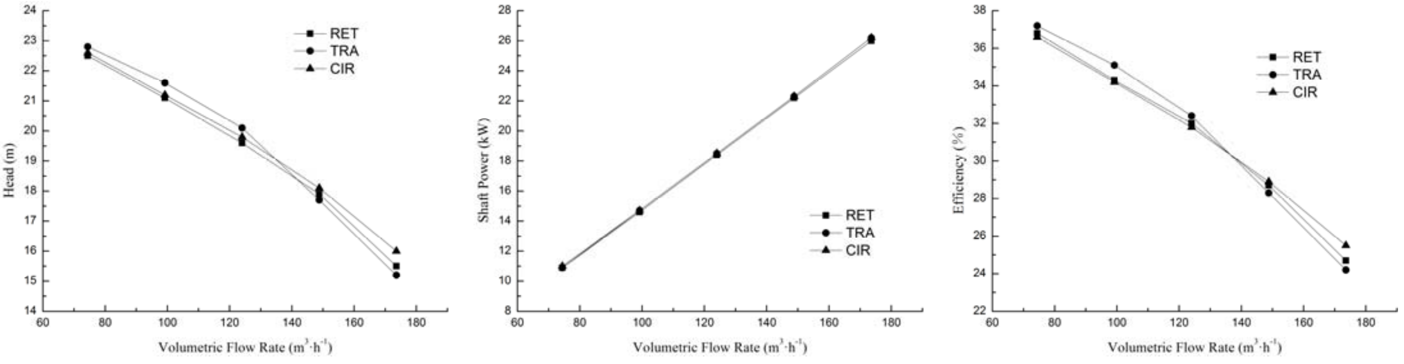


Fig.9. Three kind of cross-sectional shape

3D flow numerical simulation and external characteristic curves prediction had been conducted for 18 thrust-ring-pump's flow passage models as listed in Table 2, and external characteristic curves of scheme A are shown in Figure 10. It shown that when the 6 kinds of hole patterns match with oil bath with RET and CIR shape, there are only tiny differences in the pressure and the efficiency. Only when the 6 kinds of hole patterns match with oil bath withTRA shape, the head and efficiency go up small at the condition of small discharge, and the head and efficiency go down small at the condition of large discharge. Shaft power is almost the same when the cross-sectional shape change.



(a) (b) (c)

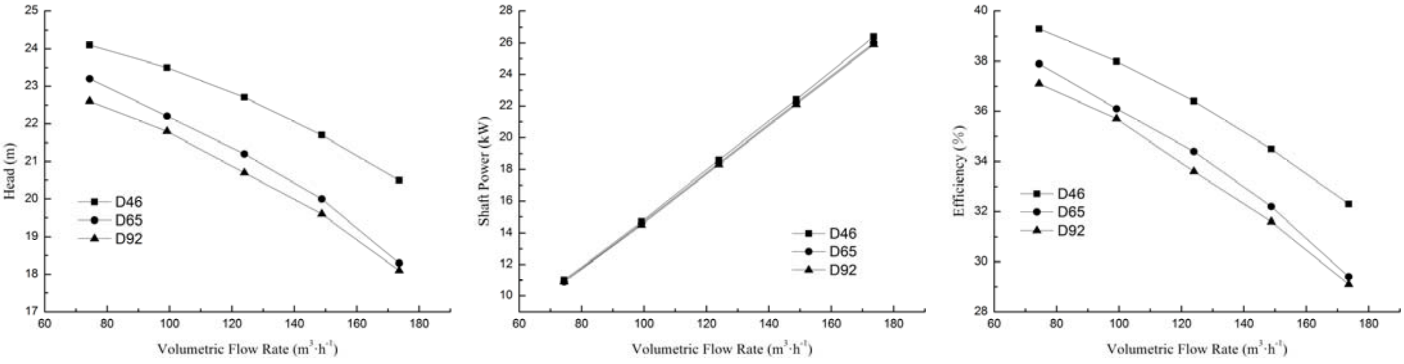
Fig.10. Performance curves of curves of scheme A with 3 kinds of cross section.

All the models in the table 2 were calculated. Through comparative analysis, it is shown that the cross-sectional shape of the oil bath only has little influence on the performance of thrust-ring-pumps with the other hole patterns. Therefore, in the design process of the oil bath, the manufacturing process is only needed to be considered without considering the influence from the cross-sectional shape.

4.2 **Outlet area of oil bath**

The outlet diameter of oil bath is one of the geometrical parameter closely relating to thrust-ring-pump's hydrodynamic performance, the outlet diameter of oil bath for the original test pump model (scheme A) is Φ65 mm. In order to analyze the impact of outlet area of oil bath on thrust-ring-pump's performance, we assumed that the outlet area is changed into half and double of the original and the corresponding outlet diameter are Φ46 mm and Φ92 mm respectively. Excepting the outlet area of oil bath, the other geometrical parameters of model are unchanged.

The predicted external characteristic curves by means of 3D flow numerical simulation are shown in figure 11for thrust-ring-pumps with outlet diameter of Φ46 mm (D46), Φ65 mm (D65) and Φ92 mm (D92). From figure 11(a) and figure 11(c), it can be seen that the head and efficiency of the pump increase greatly if outlet diameter of oil bath is Φ46 mm, while the head and efficiency of the pump decrease a little if outlet diameter of oil bath is Φ92 mm. From the figure11(b), it is noticed that the shaft power increases a little as outlet area reduces half, while the shaft power almost no change as outlet area increases one time.



(a) (b) (c)

Fig.11. Performance curves of thrust-ring-pumps with different outlet areas.

5. Optimization Design of Thrust-Ring-Pump for One Large Hydroelectric Unit

Based on the above calculation and analysis, the flow passage of original test pump model (scheme A) has been optimized. To guarantee thrust-ring-pump's hydrodynamic performance, the holes inside thrust ring must match oil bath well, so the size of oil bath at axial direction shouldn't be too small and should be larger than the diameter of holes inside thrust ring at least. Since the diameter of the holes inside thrust ring is Φ40mm, the outlet diameter of oil bath was set Φ50 mm and gradually increases up to Φ92 mm after 3D flow numerical simulation and performance prediction of multi-scheme thrust-ring-pump had been conducted. In order to further reduce the total area of oil bath and simplify the structure, the number of outlet is decreased from 8 to 2. In this way, it can not only ensure the size of oil bath at axial direction, but also reduce the total area of oil bath and simplify its structure. Figure12 shows 3D model of optimized flow passages. Figure 13 shows the performance curves of both before and after optimization, and it proved that the performance of optimized thrust-ring-pump has greatly enhanced.

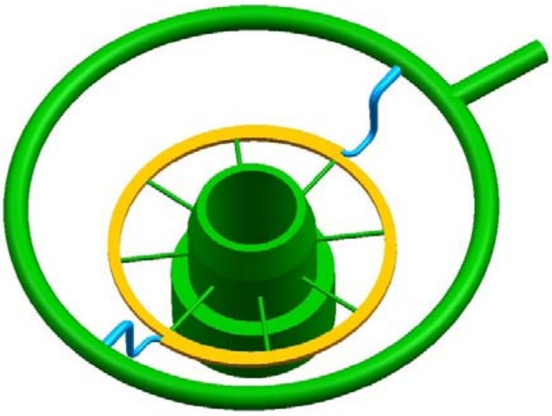
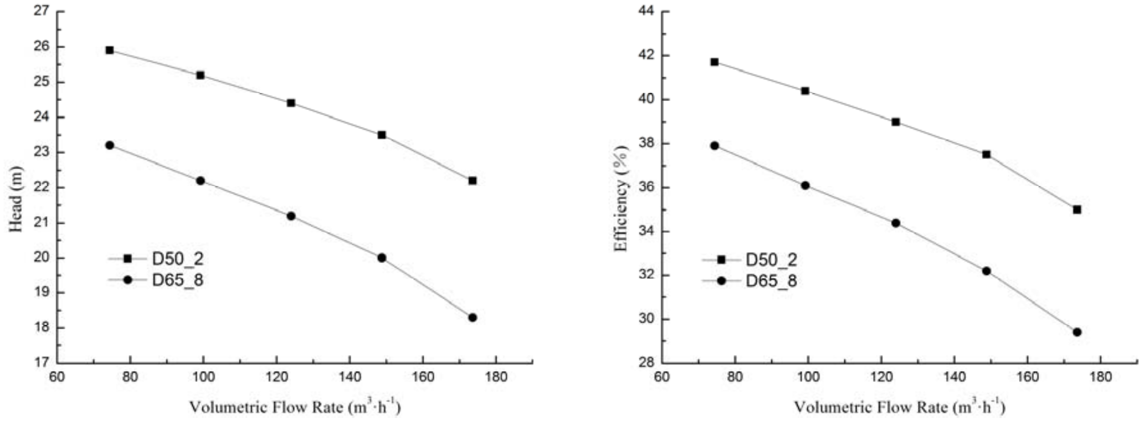


Fig.12. Three-dimensional model of the optimized flow passages



(a) (b)

Fig.13. Performance curves of both before and after optimization

6. Conclusion

Thrust-ring-pump is a kind of extreme-low specific speed centrifugal pump which has very special structure with numerous restrictions from thrust bearing and operation conditions of hydro-generator unit. It should not only focus on itself but also take the pipes and other components of circulating and cooling systems into account during the design of thrust-ring-pump. A collaborative hydrodynamic optimization methodology for thrust-ring-pump and the oil circulating and cooling system has been presented with 3D flow numerical simulation and performance prediction. For design of a thrust-ring-pump, you should pay attention to:

(1) To accurately determine the hydrodynamic parameters for the design of thrust-ring-pump, the hydrodynamic loss characteristics curves of the oil circulating and cooling system of thrust bearing should firstly calculated with 1D flow numerical simulation based on the layout of oil lubricating and cooling systems system for hydro turbine units at the power plant.

(2) Although there has some differences in the performance curves between the prediction based on 3D flow numerical simulation and the test results, it is feasible to use the numerical simulation technology to analyze and optimize the flow passage of thrust-ring-pump.

(3) The flow passage matching between the holes inside thrust ring and oil bath has great impact on thrust-ring-pump's hydrodynamic performance. In the design of oil bath, you can select the cross-sectional shape of oil bath by only considering convenient in manufacturing. If the structure allows, the total area of oil bath should be reduce properly. In order to reduce the losses, the type and diameter of outlet pipe should be chosen carefully.

Acknowledgments

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