Review and optimization of main parameters of pump turbine in Xiangshuijian pumped-storage power station

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Abstract. Mixed transportation technology of oil and gas is an efficient transportation method of offshore oil fields, in which oil and gas multiphase pump is the key equipment. In this paper, aimed at a single compression stage unit of a helico-axial multiphase pump prototype, a numerical simulation of internal flow field is carried out. It is assumed that the flow is steady and the two-phase flow pattern is bubble flow. Water is the main phase and incompressible air is the second phase. The change of external characteristics is compared in different inlet gas volume fraction (GVF) condition; the internal flow field characteristics such as velocity fields, pressure fields, and two-phase distributions are discussed as well. The result shows that the differential pressure and the hydraulic efficiency decrease with the increase of GVF, and there are some significant changes in internal flow fields. Further, under the condition of 10% inlet GVF, the changes of external characteristics and internal flow field of the pump when the air bubble diameter varies are compared. The result shows that the differential pressure and the hydraulic efficiency decrease with the increase of bubble diameter.

1. Summary
Xiangshuijian pumped-storage power station is a pure daily regulation pumped-storage power station located in Eqiao town, Anhui province. It will undertake the task of peak shaving, valley filling, frequency modulation, phase modulation and spare for accident in the East China power grid system. The station is equipped with 4 vertical shaft single stage reversible Francis turbine units with each unit capacity of 250MW.

The basic parameters of the power station are as follows:

Table 1. Level

|                  | Upper reservoir | Lower reservoir |
|------------------|-----------------|-----------------|
| Design flood level(m) | 222.8           | 14.96           |
| Design normal level(m) | 222             | 14.6            |
| Normal operating level(m) | 198.0        | 12.44           |
| Dead water level(m)     | 190             | 1.95            |

Table 2. Storage capacity and corresponding pool level

|                                | Upper reservoir | Lower reservoir |
|--------------------------------|-----------------|-----------------|
| Effective storage capacity for normal operation ($10^6 m^3$) | 10.5            | 10.5            |
Corresponding pool level variation (m)  222~198  1.95~12.44
Accident reserve capacity (10^6 m³)  2.32  2.32
Corresponding pool level variation (m)  198~190  12.44~14.6

Table 3. Head/lift

| Minimum gross head/lift (m) | 185.56 |
|-----------------------------|--------|
| Limit minimum gross head/lift (m) | 175.4 |
| Maximum gross head/lift (m) | 220.05 |
| Rated head under generator mode (m) | 190 |

The reservoir area of the upper reservoir is small, and the vegetation is better. The sediment passing through the turbine mainly comes from the lower reservoir, and the annual average suspended sediment content of water flowing into the lower reservoir is 0.023 kg/m³.

2. Main parameters of pump turbine in feasibility study review stage

Main parameters selection of pump turbine in feasibility study review stage are shown in table 4:

Table 4. Expected pump turbine parameters of Xiangshuijian power station during feasibility study review stage

| Unit capacity       | 250MW         |
|---------------------|---------------|
| Unit speed          | 250 r/min     |
| Runner diameter     | 5.09 m        |
| Suction head Hs     | -58 m         |
| Installation height of unit | -56.05m |

Turbine mode

| Head (m) | Max. head (full load) | Rated head (full load) | Min. head (normal operation) | Min. head (Reserve operation) |
|----------|------------------------|------------------------|------------------------------|------------------------------|
|          | 217.4                  | 190                    | 182.1                        | 172.2                        |
| Turbine efficiency (%) | 92.52               | 90.5                   | 90.2                         | 90                           |
| Output/Input (MW)     | 253.81                | 253.81                 | 237.27                       | 216.57                       |
| Flow (m³/s)           | 128.63                | 150.47                 | 147.25                       | 142.45                       |
| Turbine specific speed (m-kW) | 178.55            |
| Turbine specific speed coefficient | 2461            |

Pump mode

| Lift (m) | Max. lift | Min. lift (after normal generation) | Min. lift (after spare generation) |
|----------|-----------|-------------------------------------|------------------------------------|
|          | 222.3     | 189.2                               | 179.5                              |
| Pump efficiency (%) | 92.5     | 92.8                                | 92.2                               |
| Output/Input (MW)   | 245.28    | 262.95                              | 268.14                             |
| Flow (m³/s)         | 104.04    | 131.47                              | 140.54                             |
| Pump specific speed (m·m³/s) | 44.29   | 56.20                               | 60.44                              |
| Pump specific speed coefficient | 2550    | 2867                                | 2964                              |
3. Review and optimization of main parameters of pump turbine

In order to realize localization of the equipment in Xiangshuijian pumped-storage station, the equipments were purchase between Harbin Electric machinery Co., Ltd (HEC for short) and Dongfang Electric Machinery Co, Ltd (DEC for short) by bidding and negotiation. And the equipment were designed and manufactured by HEC or DEC independently. Therefore, Powerchina Huadong Engineering Corporation consulted with a number of unit manufacturers once again during bidding stage, conducted in-depth exchanges with HEC and DEC, reviewing and further researching the main technical parameters especially the Suction head and installation elevation of Xiangshuijian power station during feasibility study review stage.

3.1. Rated speed and Specific speed

Due to further review and manufacturer’s recommendation, the rated speed is identified as 250r/min. The unit specific speed and specific speed coefficient are a comprehensive index to describe the technical and economic performance of the unit. As the specific speed increases, the unit synchronous speed will improve, the weight of unit, the cost and dimensions of the plant will reduce. But the higher specific speed requires higher cavitation characteristics of the unit. For pumped-storage units, it should meet the requirements of pump mode firstly, and should consider the turbine mode at the same time.

According to the statistics and analysis of reversible pump turbine parameters from domestic and foreign, built and under built power station which head is between 200m and 300m, and calculated according to the statistical formula and recommended parameters from manufacturers, and considering the head variation of this power station ($H_{p_{max}}/H_{min}=1.291$), the unit parameters should not be too high. The pump specific speed under the average lift of unit is about 50 m.m3/s, and the corresponding $K_p$ value is 2734; The pump specific speed of pump mode is between 44.29 m.m3/s and 60.44m.m3/s, and the corresponding pump specific speed coefficient value is between 2550 and 2964; the specific speed of turbine mode under rated head is 178.55m-kW, and the corresponding specific speed coefficient $K_t$ is 2461.

3.2. Maximum input power of pump mode

When determining the maximum input power of a pump with minimum lift, the following factors should be considering:

- In order to make full use of motor capacity and make the apparent power under generating condition and pumping condition approximately equal, the generator power factor $\cos\phi_g$ under generating condition is set to 0.9, and motor power factor $\cos\phi_m$ is set to 0.98 under pumping condition.
- The efficiency of the generator motor has allowance, and under the pumping condition, efficiency is not less than 98.5%.

Based on the maximum pump input power at the frequency of 50Hz during bidding stage and considering the normal frequency changes (49.8-50.5Hz under pumping condition) to ensure the safe and stable operation of the unit, the maximum shaft input power of pump should not be greater than the maximum allowable shaft output power of generator motor (less than 268MW). It is required that the manufacturers of the units should be fully consider the possible error of input power between model and prototype, and the input power should match the maximum allowable shaft output power of generator motor.

3.3. Weighted average efficiency

The unit in the power station will be designed by HEC or DEC independently. During bidding stage, it is required that the weighted average efficiency should be not less than the middle international level. So based on the consulting of seven manufacturers, as well as the weighted factor provided by planning major, the target value of weighted average efficiency under turbine and pump mode should be not less than 90.6% and 92.7%.
The actual bidding results show that the weighted average efficiency of HEC and DEC under turbine and pump mode are both higher than above requirements. From the bidding parameters, the main domestic manufacturers have the ability to design independently on the basis of the introducing, digesting and absorbing of units of multiple pumped-storage power stations.

3.4. Suction head and installation elevation

The recommended value of Suction head (Hs) is -58m and the installation elevation is -56.05m in the feasibility study review stage in Xiangshuijian power station. During bidding stage the statistical formula was used to check and calculate the Suction head Hs of pump turbine in Xiangshuijian power station. Compared to power stations with similar head and consultation data from manufacturers, Hs and installation elevation of pump turbine in Xiangshuijian power station were optimized.

3.4.1. Checking and calculating Hs by using statistical formula. Generally, the pump cavitation under the maximum and minimum lift represent the cavitation control requirement in the whole operating range. Therefore, cavitation coefficient σp and the corresponding Suction head Hs of pump turbine under the maximum lift and the minimum lift pumping condition were checked and calculated using the statistical formula, and the calculation results are shown in table 5.

Table 5. The cavitation coefficient σp and Hs of Xiangshuijian power station calculated by the statistical formula

| Formula source | Statistical formula | Hp=179.5m (spare generation) | Hp=222.3m |
|----------------|---------------------|------------------------------|-----------|
| Beijing Institute (78-85) | σp=0.00481nq3/4.71 | nq=60.44m.m³/s | 0.2581 | -36.27 | 0.1909 | -32.4 |
| Toshiba Co (old) | Hp=10−Ks³/(1000-0.7Hpm±) | / | / | / |
| Toshiba Co (new) | Hp=10−(1+Hp/1200)(Ks³/1000) | / | -37.55 | / | -31.3 |
| R.S.Stelzer(America) | σp=0.00117nq4/3 (critical) | | 0.2775 | -39.75 | 0.1833 | -30.69 |
| R.S.Stelzer(America) | σp=0.00137nq³ (incipient) | | 0.3250 | -48.28 | 0.2147 | -37.66 |
| Stepanov(Soviet Union) | σp=0.00121nq³ | | 0.2846 | -41.03 | 0.188 | -31.74 |
| Hydropower engineering consulting company | σp=0.005249nq⁰.⁹₁₈ | | 0.2262 | -30.55 | 0.1701 | -27.75 |

Note: * Hs=10−5V/900−σpHp(m)

According to the calculation of statistics formula, the incipient cavitation coefficient and Hs of Xiangshuijian power station under the maximum and minimum lift are -37.66m and -48.28m. Considering the tail water level, the calculated installation elevation, is -35.71m.

3.4.2. Statistical calculation of Hs of similar power station. The domestic pumped-storage power station that has similar head section are Bailianhe pumped-storage power station in Hubei, Tongbai pumped-storage station in Zhejiang, Taian pumped-storage power station in Shandong, etc. The main parameters and statistical calculation results of Hs of these power station are shown in table 6.

Table 6. Comparison of main parameters and statistical calculation of Hs of pumped-storage power stations with similar head section

| Project name | Xiangshuijian | Bailianhe | Taian | Tongbai |
|--------------|--------------|-----------|-------|---------|
| Unit capacity (MW) / Rated speed (r/min) | 250/250 | 300/250 | 250/300 | 300/300 |
| Maximum/Rated/Minimum head (m) | 217.4/190/172.2 | 213.7/195/178.3 | 253/225/212.4 | 283.7/244/230.2 |
| Maximum / Minimum lift (m) | 222.3/179.5 | 222.7/191 | 259.6/223.6 | 288.3 / 237.5 |
| Hpmax/Hubin | 1.291 | 1.25 | 1.222 | 1.252 |
Hs calculated by statistical formula under maximum and minimum lift (m)

| Manufacturer | Recommended Hs (m) | Installation elevation (m) | Remark |
|--------------|------------------|---------------------------|--------|
| A            | -50              | -48.05                    |        |
| B            | -55              | 53.05                     |        |
| C            | -50              | -48.05                    |        |
| D'           | -46.95           | -45                       |        |
| E            | 34.1~71.3        | -32.15~69.33              |        |
| F            | 55.4             | -53.45                    |        |
| G            | -49.95           | -48                       |        |

It can be seen from table 3, the installation elevation of pump turbine in Xiangshuijian power station is -56.05m in feasibility study and review stage, and the allowance is larger than that of Bailianhe, Taian and Tongbai compared to the statistical formula calculation result -35.71m. In the feasibility study and review stage, the Hs of Xiangshui Jian power station is -58m, so there is a possibility of further optimization.

3.4.3. Hs recommended by various manufacturers. At the bidding stage, the main parameters, especially the Hs of units of Xiangshuijian power station were consulted again to the unit manufacturers. And 7 manufacturers have provided the recommended values of Hs and installation elevation. The main results are shown in table 7 below.

**Table 7. Hs value and installation elevation recommended by the manufacturer in the bidding stage**

| Manufacturer name | Recommended Hs (m) | Installation elevation (m) | Remark |
|-------------------|-------------------|---------------------------|--------|
| A                 | -50               | -48.05                    |        |
| B                 | -55               | 53.05                     |        |
| C                 | -50               | -48.05                    |        |
| D'                | -46.95            | -45                       |        |
| E                 | 34.1~71.3         | -32.15~69.33              |        |
| F                 | 55.4              | -53.45                    |        |
| G                 | -49.95            | -48                       |        |

The unit can run without cavitation in the whole range of operation

This value can ensure the pump turbine operate in normal range without cavitation; if the pump turbine operates in spare storage condition without cavitation, the installation elevation is required to be -54m

Recommended value under minimum lift Hs=-70m
The cavitation coefficient relationship curves provided by some manufacturers are shown in figure 1 and figure 2.

![Figure 1. Relationship between suction head and cavitation coefficient in D plant](image1)

![Figure 2. Pump operating characteristic curve of G plant](image2)
3.4.4. Recommendation of Hs and installation elevation and optimization of operation area division in bidding stage. Most of the manufacturers who provided data, recommended suction head should be above -56m, and most of them are based on the existing similar runner model, so the data can be referenced.

For instance, the model acceptance test results of Bailianhe power station which the parameters is similar to Xiangshuijian power station, show that the Suction head of -50m can ensure the safe and efficient operation of the unit (grid frequency is 49.5~50.5Hz).

In order to fully understand the Hs requirements of Xiangshuijian pump turbine, and determine the installation elevation reasonably, Powerchina Huadong Engineering Corporation had technical exchanges with manufacturers in Hs specifically. For Hs=-54m, considering the normal frequency change 49.8-50.2Hz, in the all operation head, the main conclusions of communication with the manufacturers are as following: It is believed that the Hs can ensure the stable operation of the unit without cavitation in the whole operation range.

It can ensure the stable operation without cavitation in the normal operation condition of the power station, but not in the case of accident backup. Nevertheless, it can ensure that the loss of weight caused by cavitation meets the requirements of IEC 60609 - 1:2004, and the unit can run safely and stably in this condition.

According to the above information, the Hs of Xiangshuijian unit is defined -54m and the installation elevation is -52.05m in the bidding stage. At the same time, domestic pumped-storage power station such as Tianhuangping and Guanxu, rarely use emergency reserve capacity by so far. Therefore, considering the wide head/lift variation range of Xiangshuijian pumped-storage power station and the actual situation of emergency reserve capacity, emergency reserve time was classified into the unit short-time operation range, and the operating head / lift range of power station are devided as following:

- The minimum gross head/lift under normal operation condition is 185.56m, and the corresponding tail water level is EL.12.44m.
- The extreme minimum gross head/lift is 175.4m, and the corresponding tail water level is EL.14.6m.

In order to reflect the actual operation of the power station more accurately, and make the unit operating more accord with the actual characteristics of the power station, the normal frequency range of the unit is required as follows:

- Pump mode: 49.8Hz~50.5Hz;
- Turbine mode: 49.5Hz~50.2Hz.

The guaranteed value of the normal operating frequency range is accordant with GB/T22581-2008 " Basic technical conditions of Francis pump turbine " (released in December 15, 2008, October 1, 2009)

The requirements of the cavitation performance under different operating conditions described in the bidding document are as follows:

Under the normal operating condition and the frequency of 49.8-50.5Hz, the design of the pump turbine should ensure that the incipient cavitation coefficient (σ_i) is smaller than the plant cavitation coefficient (σ_p), and that the unit should run safely and stably. Under the short-term operation condition and frequency of 49.8-50.5Hz, the design of the unit should ensure that the critical cavitation coefficient (σ_c) is smaller than the plant cavitation coefficient (σ_p) and that the unit should run safely and stably.

The short-term operation time of the power station is considered as follows: the pump mode is not more than 100h during the cavitation guarantee period and the turbine mode is not more than 50h (see IEC 60609 - 1:2004).

4. Contract values of the unit main parameters
The bidding and negotiation was based on the above reviewed and optimized parameters of Xiangshuijian power station units. Two domestic manufacturers both met the requirements of the bidding documents, and the energy index were both higher than the bidding requirements.
The units contract of Xiangshuijian power station was finally won by HEC. The main parameters in the contract are listed in table 8 below.

| Table 8. Parameters of the pump turbine (contract value) |
|---------------------------------------------------------|
| Rated output of turbine (MW)                           | 254 |
| Unit speed (r/min)                                     | 250 |
| Runner diameter D1/D2 (m)                              | 5.1387/3.28 |
| Suction head Hs (m)                                    | -54 |
| Unit installation elevation (m)                         | -52.05 |

**Turbine mode**

| Head (m) | Maximum head (full load) | Rated head (full load) | Minimum head (normal operation) | Minimum head (spare storage operation) |
|----------|---------------------------|------------------------|---------------------------------|---------------------------------------|
|          | 219.25                    | 190                    | 181.95                          | 172.07                                |

| Turbine efficiency (%) | 93.6 | 89.7 | 88.6 | 88.88 |
| Output/Input (MW)      | 254  | 254  | 233.5| 213.5 |
| Flow (m³/s)            | 127.6| 152.15| 148  | 142.3 |
| Specific speed of turbine (m-kW) | 178.55 | 2461 |
| Specific speed coefficient of turbine | 2461 |

**Pump mode**

| Lift (m) | Maximum lift | Minimum lift (after normal generation) | Minimum lift (after spare generation) |
|----------|--------------|----------------------------------------|---------------------------------------|
|          | 222.09       | 188.74                                 | 178.94                                |

| Pump efficiency (%) | 92.67 | 92.43 | 91.77 |
| Output/Input (MW)   | 245   | 260.5 | 262.5 |
| Flow (m³/s)         | 104.23| 130.32| 137.35|
| Specific speed of pump (m-m³/s) | 44.4 | 56   | 59.9  |
| Specific speed coefficient of pump | 2552 | 2854 | 2930 |

5. Conclusion

Xiangshuijian pumped-storage power station is the first domestic station installed with completely localized equipment both for designing and manufacturing. The selection of the main parameters is mainly considered to meet the safe and stable operation of the unit, and the requirements of energy index and cavitation index are also taken into account. Through the bidding design and optimization, and following the principle that the condition should be close to the actual operation condition of power station, normal frequency range of pump/turbine mode and reserve capacity operation were regulated and distinguished reasonably, and the Suction head was further optimized. These optimization measures lay a good foundation for ensuring the successful design and manufacture of the first fully localized pump turbine.

Now all units of Xiangshuijian pumped-storage power station have been well-operated for about 7 years, and all kinds of performance index meet the contract requirements basically. The comprehensive performance of the pump turbine will be tested after the actual operation of the power station, and it is also accumulate valuable experience for the localization of the pump turbine.

References

[1] Zuyan Mei, Pumped-storage Power Generation Technology, Machinery Industry Press July, 2000. ISBN 7-111-07995-7.