IOP Conf. Series: Earth and Environmental Science **163** (2018) 012088 doi:10.1088/1755-1315/163/1/012088

Numerical study on the influence of high altitude environment on hydraulic mechanical performance

B Xue, Y P Zhao, W L Liao* and Z H Li,

Institute of Water Resources and Hydro-electric Engineering. Xi'an University of Technology. Xi'an 710048. China

Corresponding auther:liaoweili2004@163.com

Abstract: Due to the difference of performance between high altitude power station and low altitude power station, environmental factors should not be neglected in the design process of turbine in high altitude area. In order to study the influence of environmental factors on the performance of hydraulic turbine. In this paper, Francis turbine in high altitude area is taken as the object of study, numerical study in considering the variation of pressure and temperature under the condition of different working condition on the performance of the turbine, and the turbine performance without considering the environmental factors were compared, when the altitude changes, the energy characteristics, cavitation performance and the flow pattern of the unit in accordance with different environmental factors are analyzed in order to reveal the influence of altitude factors on the overall performance of the turbine. The results show that when the water temperature drops, the efficiency of the unit decreases and the cavitation coefficient decreases, when the environmental pressure decreases, the efficiency of the unit increases and the cavitation coefficient increases, when considering the combined effects of temperature and pressure, the efficiency of the unit decreases at high altitude compared with the conventional condition. The results of this study will be of guiding significance to the design and operation of turbines at high altitude.

1. Introduction

At present, most of the power stations in China are located in the middle and low elevation areas, and the water temperature and pressure changes little, and have little effect on the hydraulic mechanical performance. Therefore, the temperature and pressure changes are not considered in the design. In recent years, the power stations in middle and low elevation areas are gradually saturated, while the water resources in the southwest and Tibet are rich, but the development and utilization are very few. In Tibet, the water power resources account for about 29% of the country[1], So the focus of development in recent years has been on high altitude areas. The places are grim, weather is terribly bad and difficult to develop, lack of development experience. During the design of the unit, the influence of altitude factors is not taken into consideration, which results in many problems in the operation of the developed power station.

With the increase of altitude, the temperature and atmospheric pressure will change significantly, which will greatly affect the operation of the hydraulic turbine. Wang Lili[2] calculates the exact relationship between altitude and atmospheric pressure values based on the altitude and atmospheric values of major cities in the country. Guan Dening[3] analyzed the cavitation erosion of several power stations in Tibet, explained the main causes of cavitation erosion, and proposed a method for calculating the suction height when the elevation was above 3000 m. Su Shoukun[4] conducted a survey of four Tibet power plant, found that reduce the cavitation not only considering the suction height but also should take care of water temperature, flow, speed and sediment erosion operation, integrated a number of reasons to determine the height of aspiration. Zhao Qinming and Chen Zuwen[5] proposed the design unit in Alpine high altitude area should pay attention to modify the relative acceleration of gravity, suction height, minimum draft inlet pressure and altitude, and generator ventilation and insulation design should consider the effects of altitude and temperature, and decrease the wheel speed and the ratio coefficient of speed ratio in the design, to ensure that the unit will be able to stable operation in operation. Liu Wei[6] carried out numerical simulation of Laohuzui Hydropower Station in Tibet, the turbine internal flow field and velocity field were analyzed, found that the flow field distribution and the velocity distribution is reasonable, to prove the rationality of Laohuzui Hydropower Station design. Ji Shengbang[7] studied plateau turbine suction height formula, the suction height formula of "900" was discussed and found that "900" is only suitable for below the altitude of 2000m, when at an elevation of 2000~7000 meters should be 1100, at an elevation of 7000~10000 m is 1400, and the results have been applied in Dangxiong power station, operation results normal. Guohui and Wang Qianyun[8] through the CFD software for power plant of zangmu spiral, runner and draft hydraulic flow components were optimized through model tests and verify its rationality for Francis turbine with high specific speed hydraulic performance optimization design provides a reference. The cavitation corrosion of pure titanium and titanium alloys in seawater of 303, 318 and 333K was studied at rotating disk method by Hiromi, Mochizuki[9], when the seawater temperature increased, the volume loss rate of specimens was increased. Sagradi[10] proposed that the temperature of liquid and the rate of deformation of materials are closely related to the degree of cavitation corrosion, and the temperature is very strong without considering the deformation of materials. Many scholars[11~14] have studied the temperature of the maximum point of cavitation erosion rate, the results obtained by different scholars are different, both between 40~55 degrees centigrade.

Based on the above research situation, this paper takes the Francis turbine of a hydropower station in high altitude area as the object of study, study the influence of high altitude environment factors on the performance of hydraulic turbine, under the three condition of temperature, pressure and combined action of temperature and pressure, the numerical simulation is carried out under three working condition, including rated condition, 90% output condition and 50% output condition, when the altitude changes, the energy characteristics and cavitation performance of the unit and the flow pattern of the unit with different environmental factors are analyzed in order to reveal the influence of altitude factors on the overall performance of the turbine. The results of this study will be of guiding significance to the design and operation of turbines at high altitude.

2. Environmental parameter change and regularity analysis

As the altitude increases, the environmental pressure and temperature, and the vapour pressure change very violently. As shown in Figure 1, the research station is located in the red spot, above the altitude of 3000 m, with an average annual pressure of 67.49 kpa. Small changes in altitude in the middle area of China, the change of temperature and pressure factors can be ignored in power plant design, and in Tibet, Yunnan and other places with high altitude, especially altitude in Tibet are between 2500~5000m, therefore altitude caused by changes of pressure and temperature cannot be ignored.

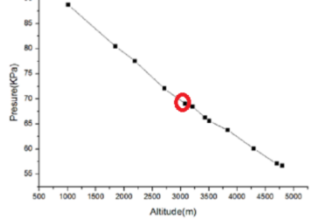


Figure 1. Relationship between altitude and barometric pressure

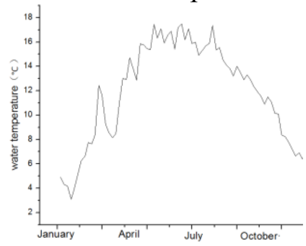


Figure 2. Relationship between water temperature and time

The power station is in the southern part of Tibet, the summer temperature is between10~25 degrees Celsius, the winter temperature is between -20~-10 degrees Celsius, the average temperature varies greatly, while low temperature season is longer, so the water temperature is greatly affected, figure 2 is the annual water temperature variation curve of the power station, this is January 2017 to December 2017 acquisition of spiral case at the average temperature of each day, as you can see from the chart, the water temperature is lowest in January, and the average water temperature in January 15, 2017 is only 3 degrees Celsius. The temperature is higher between June and September, and the water temperature is between 14~17 degrees Celsius, by years of power plant monitoring of temperature data, the annual average water temperature is 10 degrees centigrade.

As can be seen above, the average annual air pressure of the power station is 67.49 kPa, and the annual average temperature is 10 degrees Celsius. And the atmospheric pressure and water temperature of the stations in lower altitude area are much higher than this value. Therefore, the design of power stations in high altitude areas cannot fully refer to the design standards of inland power stations, and ignore the influence of water temperature and air pressure on the design of power plants.

3. Calculation model and numerical simulation method

3.1. Calculation model and hydraulic turbine parameters

The research object of this paper is a Francis turbine. The main performance parameters are as follows:

Table 1. Introduction of unit basic parameters

name	value
Rated flow	178.33 m^3/s
Rated lift	57.3 m
Rated speed	136.4 rev/min
Suction height	-6.33 m
Diameter of runner	4.596 m
Blade number of runner	13
Stationary guide vane	24
Guide vane	24

By using UG software for three-dimensional modeling of the turbine, under the condition that the other geometric parameters of the hydraulic turbine are constant, a wicket model with different degrees of opening is established, guide vane opening are 34.5 degrees, 29 degrees and 18 degrees, three working condition are respectively rated output, 90% output and 50% output condition. The calculation model is shown in figure3.

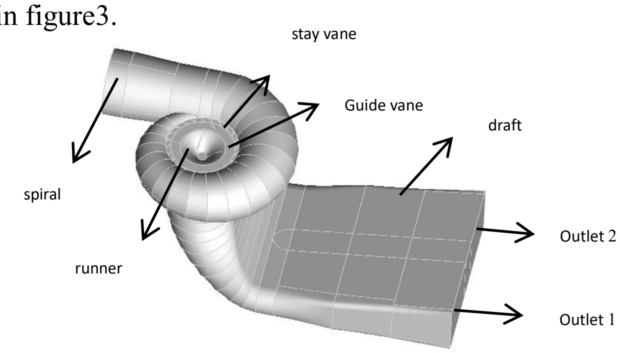


Figure 3. Geometric model

3.2. Mesh generation

In this paper, the mesh structure of the model is divided by ICEM, and the side wall have been encrypted, and the mesh to be independent verification of figure 4 shows the relationship between the number of grid and the head, can be obtained when the grid number reached about 680 ten thousand, the head gradually stabilized, in order to reduce computation time while ensuring the accuracy of the calculation results. Here, select the 680 ten thousand grid. The number of grids between the spiral and the draft is 148, 117, 115, 169 and 139 ten thousand, respectively. The mesh of the calculation domain is shown in figure 5.

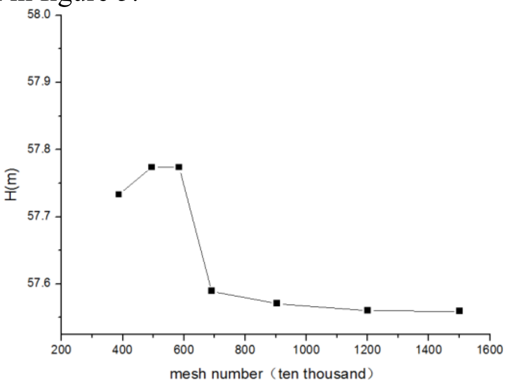


Figure 4. Relationship between mesh number and water head

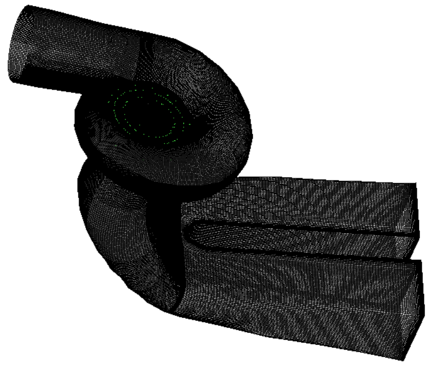


Figure 5. Structured mesh

3.3. Numerical method

3.3.1. Governing equation. Numerical calculations using the Newton incompressible fluid continuity equation and the momentum conservation equation (Navier-stokes) are as follows.

Continuity equation:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$

Momentum conservation equation:

$$\rho\frac{Du_i}{Dt} = \rho F_i - \frac{\partial \mathrm{p}}{\partial x_i} + \frac{\partial}{\partial x_i}[\mu(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_j})] + \frac{\partial}{\partial x_i}(\lambda\nabla\cdot \mathrm{v}) \tag{2}$$

F_i is the unit mass force of mass force on three axes; ρ is fluid density; u_i and u_j are absolute velocity components; p is pressure.

The turbulence model is based on the Reynolds equation of time motion and the equation of fluctuating motion. A set of closed equations describing the mean of turbulence is established for theoretical calculation.

3.3.2. Calculation parameter setting

Table 2. Modification of water temperature parameters

Tempreture(℃)	10	25
Density(kg/m³)	999.7	997
Dynamic Viscosity(kg/m/s)	1.306×10¯3	8.899×10¯4
Thermal Expansivity(K¯¹)	8.8×10¯5	2.57×10¯4
Thermal conductivity(W/m/K)	0.581994	0.6069

In this paper, CFX is applied to the numerical simulation of the model, and the turbulence model is chosen as the standard k- epsilon model, boundary condition selected mass flow inlet, considering the density change caused by water temperature, therefore, under the same opening, the mass flow at the entrance is different and the volume is the same,specific water temperature parameters are set out in table (2). The exit selects the pressure parameter, when the pressure is not considered, the outlet pressure is 255.925 kPa, and the value is 222.09 kPa when the pressure change is taken into account, the reference pressure is 0atm, and the non-slip wall condition is adopted on the side wall. The wheel speed is set to 136.4 rev/min, and the other components are set to rest. The method of calculation is constant calculation, time scale control is set as physical time step, the value is 0.001, the residual type is set to the maximum residual, the target value is 10^{-1} s.

3.3.3. Calculation condition setting. The research object of this research is the hydraulic turbine and its actual operation in a power station, the average annual water temperature of the station is 9.56 degrees, and the actual pressure of the power station is 67.49 kPa. The effects of temperature and pressure are considered separately and synthetically, the performance characteristics of the hydraulic turbine are analyzed under the rated condition (34.5 degrees of the guide vanes angle), the 90% output condition (28 degrees of the guide vanes angle) and the 50% output condition (19 degrees of the vane angle), see Table 3 for details.

Table 3. Calculation condition setting

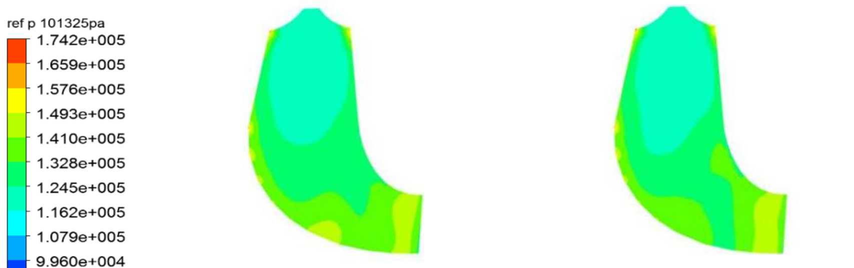
Code	Condition	T(℃)	P(kPa)
a	Routine calculation	25	101.325
b	Consider temperature	10	101.325
c	Consider pressure	25	67.49
d	Comprehensive consideration	10	67.49

4. Performance analysis

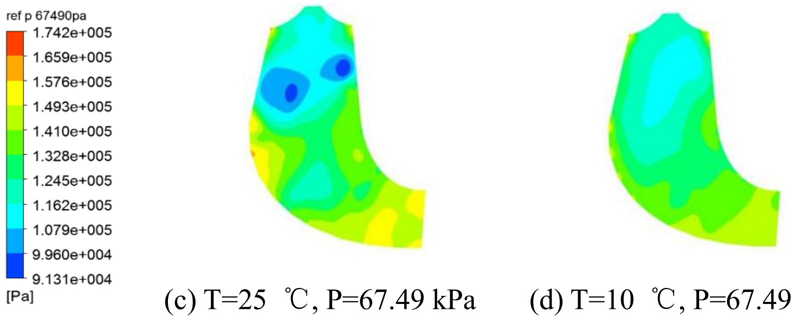
Under different condition of opening, temperature and pressure, the fixed length turbulence calculation is carried out. The following three cases are analyzed, which are the rated condition, the 90% output condition and the 50% output.

4.1. Analysis of internal flow field

The following is the pressure contour of the draft-inlet to elbow section at 50% output, figure 6 (a) and (b) reference pressure is 101.325 kPa, figure 6 (c) and (d) reference pressure is 67.49 kPa, when the pressure decreases,the low pressure area in straight-cone-section of the draft increases obviously, and the cavitation is easy to occur. When the temperature is lower, the low pressure area decreases, while the temperature decreases, the saturated vaporization pressure of water becomes smaller, and the water temperature decreases, which is beneficial to improve the cavitation performance and reduce the cavitation area of the turbine.



(a) T=25 ℃, P=101.325 kPa (b) T=10 ℃, P=101.325 kPa



(c) T=25 ℃, P=67.49 kPa (d) T=10 ℃, P=67.49 kPa

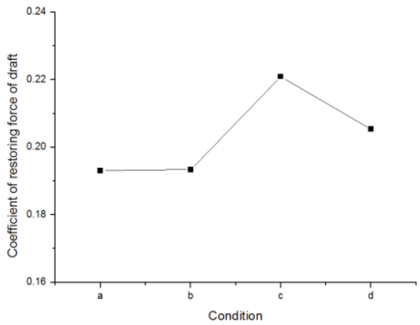
Figure 6. Pressure contour of draft inlet to elbow section

4.2. Cavitation performance analysis

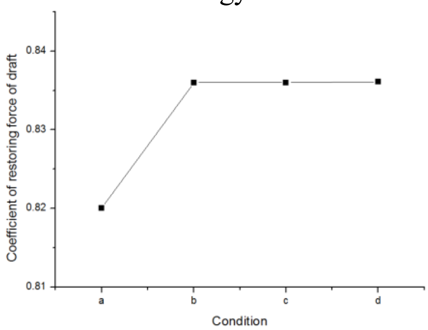
4.2.1. Calculation of restoring force coefficient of draft. Calculating equation of restoring force coefficient

$$\eta_w = 1 - \left(\frac{2gh_w + v_5^2}{v_3^2} \right) \tag{3}$$

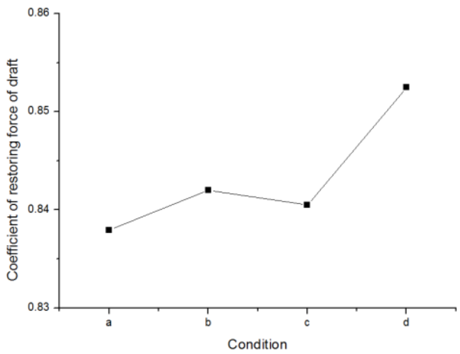
Where v_3 is the average speed of the draft-inlet, and v_5 is the average speed of the draft-outlet. The results are as follows, as shown in figure 7, the pressure and temperature of the three condition are reduced, and the restoring force coefficient of the draft is increased. Indicating that the pressure and temperature are reduced, the capacity of the draft to recover kinetic energy is enhanced.



(a) 50%output



(b) 90%output



(c) Rated output

Figure 7. Restoring force coefficient of draft under different condition

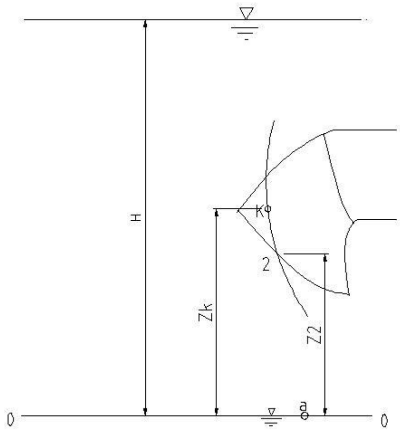


Figure 8. Flow model diagram

Figure 8 is a flow diagram of a model turbine, in which the K point is the lowest point of pressure on the runner blade, and the corresponding pressure value is Pk, point 2 is a point on the exit edge of the runner blade, the pressure at the corresponding point is P2, and the a is the point on the downstream surface, the pressure at the corresponding point is Pa, the downstream is open type, the Pa is the ambient pressure. The Bernoulli equation is used to represent the relative motion of the K point and the 2 point.

$$\frac{p_K}{r} + Z_K + \frac{w^2{}_K - u_K^2}{2g} = \frac{p_2}{r} + Z_2 + \frac{w^2{}_2 - u_2^2}{2g} + \Delta h_{K-2} \tag{4}$$

Where *w* represents circumferential speed, *u* is relative velocity, Zi represents the height of the i point to the reference point, Δh_{K-2} represents the hydraulic loss of K point to 2 point,

The Bernoulli equation is used to represent the relative motion of the a point and the 2 point.

$$\frac{p_2}{r} + Z_2 = \frac{p_a}{r} + Z_a - \frac{v_2^2}{2g} + \Delta h_{2-a} \tag{5}$$

Where v is absolute speed,

From the above two equations and other condition can be derived

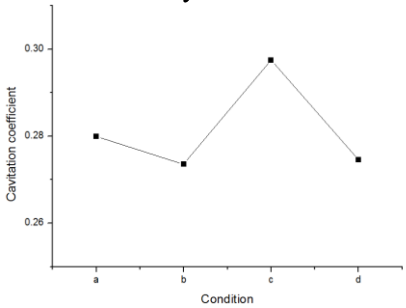
$$\frac{p_k - p_v}{rH} = \frac{\frac{p_a}{r} - \frac{p_v}{r} - H_s}{H} - \left(\frac{w_K^2 - w_2^2}{2gH} + \eta_w \frac{v_2^2}{2gH}\right) \tag{6}$$

where $H_s = Z_K - Z_a$, $\eta_w = 1 - \frac{2g\Delta h_{2-a}}{v_2^2}$.

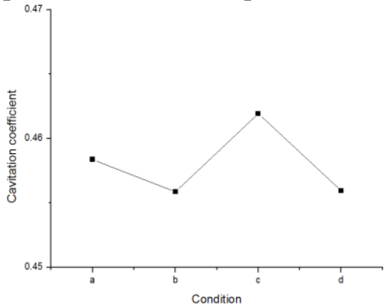
here
$$\sigma = \left(\frac{w_K^2 - w_2^2}{2gH} + \eta_w \frac{v_2^2}{2gH}\right) \tag{7}$$

$$\sigma_p = \frac{\frac{p_a}{r} - \frac{p_v}{r} - H_s}{H} \tag{8}$$

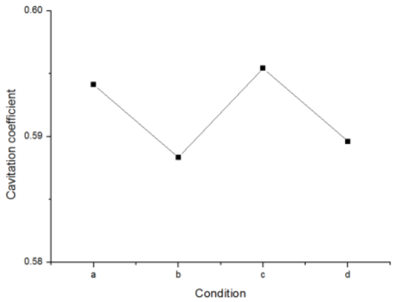
Where σ is the cavitation coefficient of hydraulic turbine, and the σp is the cavitation coefficient of hydropower station. The cavitation coefficient calculated by the formula in each condition, as shown in figure 9, under three condition: reduce water temperature, the cavitation coefficient of turbine will reduce, only to reduce the environmental pressure, the cavitation coefficient of turbine will increase, when the water temperature is 10 ℃, the air pressure is 67.49 kPa, the cavitation coefficient is smaller than normal. The cavitation condition of the hydraulic turbine is that the cavitation coefficient of the hydropower station is greater than or equal to the cavitation coefficient of the hydraulic turbine, the lower water temperature can reduce the degree of cavitation, and the lower environmental pressure is not conducive to cavitation performance, the lower the pressure, the more likely cavitation occurs. The combined influence of the actual pressure and water temperature of the power station will reduce the cavitation coefficient of the hydraulic turbine and improve the cavitation performance.



(a) 50%output



(b) 90%output



(c) Rated output

Figure 9. Cavitation coefficient of runner under different condition

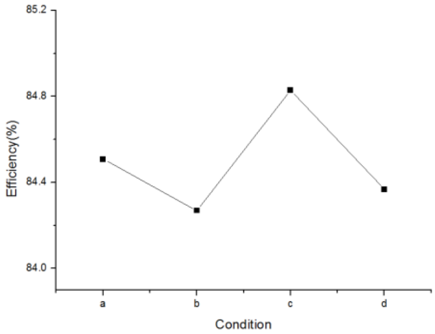
4.3. Analysis of unit external characteristics

The relationship between volumetric flow and efficiency under different condition is analyzed in this paper. In CFX calculations, the efficiency formulas are as follows

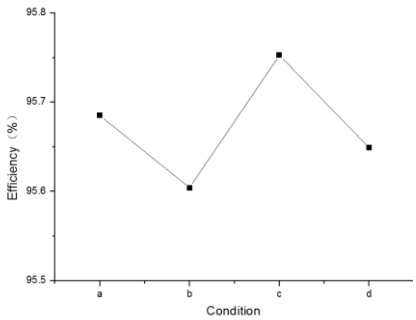
$$\eta = \frac{M\omega}{\gamma QH} \tag{9}$$

Where $\gamma = \rho g$, is water severe, ρ is the density of water, g is the acceleration of gravity, the value is g=9.81 m/s².

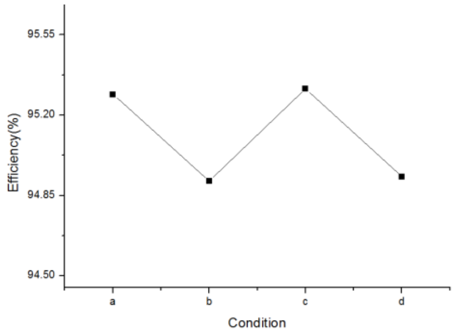
The calculation results under the three condition are shown in figure 10



(a) 50%output



(b) 90%output



(c) Rated output

Figure 10. Efficiency value under different condition

The figure shows: under rated condition, 90% output condition and 50% output condition, considering the temperature and pressure condition compared with the conventional condition, the temperature is reduced, the unit efficiency decreased; when the pressure is reduced, the efficiency increased,which is due to the decrease of air pressure, the recovery coefficient of the draft of the hydraulic turbine increases, and the recovery kinetic energy capability is enhanced, considering the temperature and pressure, the efficiency is lower than the conventional conditions, higher than the lower temperature conditions. This shows that under the same condition to reduce environmental pressure can improve the unit efficiency, reduce the spiral-inlet-water temperature will reduce the efficiency of the unit, for the environment of the power station, the environmental factors (pressure and temperature) are combined to reduce the efficiency of the unit.

5. Result

Considering the temperature and pressure changes caused by altitude, the steady numerical simulation of full flow field of a No.4 machine in a high altitude area is carried out. The actual station pressure and temperature as the basis, from four aspects of conventional condition, temperature and pressure changes, the comprehensive effect, respectively on the rated condition, 90% output condition, 50% output condition are calculated, analyzed the effect of high altitude environment on water conservancy machinery properties, the results are as follows:

When the environmental pressure decreases, the low pressure area of the elbow section of draft becomes larger, cavitation is prone to occur, the water temperature decreases, the low-pressure area is also decrease, and the saturation vaporization pressure becomes smaller, which is beneficial to improve cavitation performance. With the decrease of water temperature and pressure, the restoring force coefficient of the draft tube is increased, and the recovery kinetic energy capacity is enhanced. At the same time, the cavitation coefficient of hydraulic turbine decreases with the decrease of temperature, which is beneficial to the improvement of cavitation performance. The environmental pressure decreases, the cavitation coefficient increases, and cavitation is more prone to occur.

As the rise of altitude, the air pressure decreases and the efficiency increases; as the water temperature decreases, the efficiency of the turbine decline; when the pressure drops to 67.69 kPa and the water temperature drops to 10 degrees centigrade, the efficiency is lower than normal.

Acknowledgments

The authors would like to thank Natural Science Foundation of China (No.51679196) and Scientific research project of Shaanxi Provincial Education Department (No.17JK0568) and for their financial support.

References

[1] Zhuo Maqiongda. Tibet hydropower station construction on prevention of turbine cavitation and cavitation technology. Electromechanical Technology of Hydropower Station, 2012,

35(1):13-16.
[2] Wang Lili. Regression Calculation of the Relationship between Altitude and Atmospheric Pressure. Value Engineering, 2014, 23(2):324-325.
[3] Guan Deling. Discussion on cavitation erosion of hydraulic turbines in Tibet Plateau. Advances in water conservancy and Hydropower Engineering,1996. 16(3), 58-61
[4] Su Shoukun. Discussion on turbine cavitation in high altitude area. Journal of Shenyang Agricultural University, 1998-01, 29(1):79-81.
[5] Zhao Mingqin, Chen Zhuwen. Discussion on Design of giant hydraulic turbines in alpine and high altitude areas. Yangtze River, 2013, 44(9):93-96.
[6] Liu Wei, Luo Hongying, Yu Qiang, et al. Numerical simulation of internal flow field of water turbine in Tibet Lao Hu Zui power station. Hydropower and Rural Electrification, 2015, 18(4):59-62.
[7] Ji Shengbang. Calculation of allowable suction height of hydraulic turbines in plateau area. Hydropower Station Design, 1992，8(3):42-45.
[8] Shao Guohui, Wang Qianyun. Optimized design of high speed Francis turbine for Zang Mu Hydropower Station. Water Science and Engineering Technology, 2013,3(5):52-56.
[9] Hiromi Mochizuki, Motohiro Yokota, Shuji Hattoori. Effects of materials and solution temperatures on cavitation erosion of pure titanium and titannium alloy in sea water[J]. Wear, 2007, (262):522-528.
[10] D Pulino-Sagradi, A M M Nazar, J J Ammann, et al. Effect of temperature and strain rate on cavitation in a superplastic duplex stainless steel[J]. Elsevier Science Ltd, 1997, 45(11):4 663-4 666.
[11] Liu Xiumei. Effect of liquid parameters of laser cavity and collapse[D]. NanJing:Nanjing University of Science and Technology, 2009.
[12] Shuiji Hattori, Yuki Goto, Takaki Fukuyama. Influence of temperature on erosion by a cavitating liquid jet[J]. wear, 2006, (260):1 217-1 223.
[13] C T Kwok, H C Man, L K Leung. Effect of temperature, PH and sulphide on the cavitation erosion behaviour of super duplex strainless steel[J]. Wear, 1997, (211)84-93.
[14] Zhu Xiuli, Niu Yong, Huang Leiluo et al. Influence of temperature on ultrasonic cavitation sound field[J]. (Journal of Shaanxi Normal University natural science workers Edition), 2008, 36(5):35-37.