Numerical Simulation of Ice Regime Evolution of Pumped Storage Power Station in Cold Area

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Abstract. The formation, development and melt of ice in pumped storage reservoirs in cold climate are studied by numerical simulation. Based on the theory of ice hydrodynamics and the MFC module of Visual C++ 6.0, a mathematical model of ice regime of pumped storage power station in the form of dialog box was established, which includes the hydraulic calculation module, the temperature diffusion module and the ice sheet thermal fluctuation module. The model was applied in Pushihe pumped storage power stations and the results showed that the simulation results were in good agreement with the prototype observation results. The research results can provide effective technical reference for the selection of anti-ice operation mode and the reserve of frozen storage capacity of pumped storage power station in cold area in winter.

1. Introduction
Freezing is a common natural phenomenon in cold areas. At present, China is vigorously developing new energy industry, and a large number of pumped storage power stations are planned in cold areas. The planning, design and operation of these pumped storage power stations encounter freezing problems to some extent.

At present, most of the research results of ice regime at home and abroad are focused on river ice and water conveyance channel ice regime, including prototype observation, experimental research and numerical simulation. In terms of numerical simulation, with the development of computer technology, scholars at home and abroad, such as belatos [1], Shen [2], Kai lin Yang [3], Zeyu Mao [4], Wang Jun [5-6], based on one-dimensional or two-dimensional mathematical model, have simulated the formation and evolution of ice plug, ice flower transportation, water flow conditions, etc., which provides an important reference for the research of river ice.

The research on the reservoir ice condition of pumped storage power station is still in the initial stage, and it is all aimed at the specific power station ice problem, and the systematic research has not been carried out. In this paper, based on the data of systematic ice prototype observation of typical pumped storage power stations in the north of China, a systematic study on the ice situation of pumped storage power stations is carried out by means of numerical simulation, in order to provide reference for the selection of anti-ice operation mode of pumped storage power stations in winter and the reserve of frozen storage capacity.
2. Mathematical Model of Reservoir Ice Regime in Pumped Storage Power Station

Based on the MFC module of Visual C++6.0, a mathematical model of reservoir ice condition of pumped storage power station in the form of dialog box is established. The program regards the calculation domain as a plane two-dimensional average water depth flow field for simulation. It initially has an interactive dialog box interface of human-computer interaction, and has the function of graphically displaying the simulation results of reservoir ice thickness. The mathematical model of ice regime of pumped storage power station is composed of the following three modules: (1) hydraulic calculation module; (2) temperature diffusion module; (3) thermal fluctuation module of ice sheet. The model has the interactive dialog interface of human-computer interaction, and has the function of displaying the simulation results of ice thickness in the reservoir area, including the maximum ice thickness and frozen storage capacity.

2.1. Hydraulic Calculation Module

The model control equations of the hydraulic calculation module are as follows.

Continuity equation:

\[
\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = S
\]

(1)

Momentum equation:

\[
\frac{\partial q_x}{\partial t} + \frac{\partial (uq_x)}{\partial x} + \frac{\partial (vq_x)}{\partial y} + gh\frac{\partial Z}{\partial x} + g \frac{n^2 u \sqrt{u^2 + v^2}}{h^{1/3}} = 0
\]

(2)

\[
\frac{\partial q_y}{\partial t} + \frac{\partial (uq_y)}{\partial x} + \frac{\partial (vq_y)}{\partial y} + gh\frac{\partial Z}{\partial y} + g \frac{n^2 v \sqrt{u^2 + v^2}}{h^{1/3}} = 0
\]

(3)

In the above three formulas, \( h \) is the unit water depth, m; \( Z \) is the water level, \( Z = Z_0 + h \), m; \( Z_0 \) is the bed elevation, m; \( S \) is the source sink term, m/s; \( q_x, q_y \) are the unit discharge in \( x, y \) direction, and \( q_x = hu, q_y = hv \), \( m^3 \cdot s^{-1} \cdot m^{-1} \); \( u, v \) are the average velocity in \( x, y \) direction, m/s; \( n \) is the roughness; \( g \) is the acceleration of gravity, \( g = 9.8 \) m/s\(^2\).

In the process of water inflow and outflow, the water level in the reservoir area of pumped storage power station rises or falls as a whole, so the dynamic boundary treatment technology, namely the dry and wet bed surface problem, must be involved in the simulation calculation. The moving boundary refers to the boundary between the area with water and the area without water in the plane calculation area. With reference to the method of dynamic boundary treatment in the process of flood flow, on the premise that all the dry and wet grids are included in the calculation area, the dynamic boundary treatment technology mainly considers that the grids in the whole calculation area are involved in the calculation, and the "level tiled" method is adopted to transform the dynamic boundary problem into the grid dry and wet problem. It should be pointed out that, because all grids are involved in the calculation, for the simulation calculation with a large number of grids, we should try our best to eliminate the grid that water flow can never reach, so as to reduce the waste of calculation.

2.2. Temperature Diffusion Module

For the calculation of heat conduction and temperature diffusion, the energy conservation equation needs to be solved as follows:

\[
\frac{\partial (\rho T)}{\partial t} + \text{div}(\rho u T) = \text{div}\left(\frac{k}{C_p} \text{grad}T\right) + S_f
\]

(4)
Where: \( C_p \) is the specific heat capacity, and the specific heat capacity of water is generally 4200 J\( \cdot \)kg\(^{-1} \)\( \cdot \)°C\(^{-1} \); \( T \) is the temperature, \( k \) is the thermal conductivity of the fluid, and the thermal conductivity of the general water body is about 0.55 J\( \cdot \)m\(^{-1} \)\( \cdot \)°C\(^{-1} \)\( \cdot \)s\(^{-1} \); \( S_T \) is the internal heat source of the fluid and the heat energy converted by the fluid mechanical energy due to viscosity, J.

Equation (4) is transformed into a two-dimensional control equation in the plane, the basic form of which is as follows:

\[
\frac{\partial}{\partial t} (\rho C_p h T_w) + \frac{\partial}{\partial x} (q_x \rho C_p T_w) + \frac{\partial}{\partial y} (q_y \rho C_p T_w) = \frac{\partial}{\partial x} \left( h k \frac{\partial T_w}{\partial x} \right) + \frac{\partial}{\partial y} \left( h k \frac{\partial T_w}{\partial y} \right) - S'_T
\]

Equation (5)

Where: \( T_w \) is the average water depth temperature of the unit, °C; \( S'_T \) represents the heat flux of water on the unit area, which is positive at the outlet and negative at the inlet, W. The value includes two aspects: (1) there is heat flux in or out of the water inlet unit, but not in the other units; (2) there is heat on the upper surface of the unit diffuses into the atmosphere or ice body, causing unit heat loss or ice body melting on the upper surface.

2.3. Ice Sheet Thermal Fluctuation Module

The daily variation value of ice thickness \( \Delta(h_i)_{d} \) of a pumped storage power station can be regarded as the result of the joint influence of the ice sheet and atmosphere, ice sheet and water body, as well as the heat exchange of ice sheet and solar radiation, so there is:

\[
\Delta(h_i)_{d} = A_0 \left( S_{j+1.5}^{i.5} - S_j^{i.5} \right) - \sum_{n=1}^{m} \frac{h_w (\Delta T_w)_{n}}{L_i \rho_i} \Delta t - \sum_{n=1}^{m} \frac{(\Delta R)_n}{L_i \rho_i} \Delta t
\]

Equation (6)

Where: \( A_0 \) is the degree-day-method empirical coefficient, m\( \cdot \)d\(^{0.5} \)\( \cdot \)°C\(^{-0.5} \); \( S = \int T_u (t) dt \), which is called the absolute value of negative accumulated temperature, i.e. the absolute value of the accumulated sum of negative atmospheric temperature (°C), \( T_u \) is the temperature (°C), \( t \) is the time (d); \( j \) is the days entering the ice age, d; \( L_i \) is the latent heat of ice or melting ice, generally 3.36 \times 10^5 J\( \cdot \)kg\(^{-1} \); \( \rho_i \) is the density of ice, \( \rho_i = 0.9 \times 10^3 \) kg\( \cdot \)m\(^{-3} \); \( h_w \) is the convective heat transfer coefficient between ice sheet and water body, J\( \cdot \)m\(^{-2} \)\( \cdot \)°C\(^{-1} \)\( \cdot \)s\(^{-1} \); \( (\Delta R)_n \) is the cumulative value of radiation, W.

By summing the daily variation of ice thickness according to the days of ice age, the numerical solution of ice sheet thickness in any day of ice age can be obtained. Equation (6) is the basic control equation of the ice sheet heat dissipation module of the pumped storage power station.

3. Application of Mathematical Model of Ice Regime

The upper and lower reservoirs of Pushihe pumped storage power station are taken as numerical simulation objects to carry out case application and analysis of calculation results.

3.1. Introduction of Pushihe Pumped Storage Power Station

Pushihe pumped storage power station is located in Kuandian Manchu Autonomous County, Dandong City, Liaoning Province, with the average minimum temperature in the coldest month (January) is -12.8 °C and the extreme minimum temperature is -38.5°C. The normal water level of the upper reservoir is 392.0m, the corresponding storage capacity is 11.35 million m\(^3\), the dead water level is 360.0m, the dead storage capacity is 0.95 million m\(^3\), and the total storage capacity is 12.56 million m\(^3\). The normal water level of the lower reservoir is 66.0 m, the corresponding storage capacity is 28.71 million m\(^3\), the dead water level is 62.0 m, the dead storage capacity is 16.16 million m\(^3\), and the regulating storage capacity is 12.55 million m\(^3\).
3.2. Analysis of Numerical Simulation Results of Reservoir Ice Regime of Pushihe Pumped Storage Power Station

According to the measured data of ice regime in upper reservoir of Pushihe pumped storage power station, the ice period from 2014 to 2015 is taken as the study period. Since December 1, 2014, the temperature has turned negative, so this date is selected as the starting date of ice age calculation. In addition, January 19, 2015 is defined as the last day of ice age calculation domain, with a total of 50 days. The measured meteorological data of the lower reservoir is slightly different from that of the upper reservoir, and the length of the ice age interval (December 12, 2016 to January 19, 2017) calculated in this simulation is 39 days. The daily measured meteorological data of the ice age in the calculation area of the upper and lower reservoir are shown in Table 1.

Table 1. Meteorological observation data of upper and lower reservoir of Pushihe pumped storage power station in winter of 2014-2015.

| Date       | Air temperature (°C) | Date       | Air temperature (°C) | Date       | Air temperature (°C) |
|------------|----------------------|------------|----------------------|------------|----------------------|
|            | Upper reservoir      | Lower reservoir | Upper reservoir      | Lower reservoir | Upper reservoir      | Lower reservoir |
| 2014/12/1  | -9.9                 | 2014/12/18 | -13.8                | 2015/1/4   | -2.7                 | -2.2            |
| 2014/12/2  | -12.6                | 2014/12/19 | -4.6                 | 2015/1/5   | -3.3                 | -4.4            |
| 2014/12/3  | -11.8                | 2014/12/20 | -11.3                | 2015/1/6   | -12.1                | -9.3            |
| 2014/12/4  | -12.6                | 2014/12/21 | -14                  | 2015/1/7   | -12.1                | -12.7           |
| 2014/12/5  | -13.8                | 2014/12/22 | -9.5                 | 2015/1/8   | -9.9                 | -10.7           |
| 2014/12/6  | -12.6                | 2014/12/23 | -3.6                 | 2015/1/9   | -3.3                 | -8.5            |
| 2014/12/7  | -10.6                | 2014/12/24 | -6.6                 | 2015/1/10  | -6.7                 | -8.8            |
| 2014/12/8  | -10.3                | 2014/12/25 | -9.2                 | 2015/1/11  | -8.5                 | -5.2            |
| 2014/12/9  | -8.1                 | 2014/12/26 | -7.7                 | 2015/1/12  | -9.1                 | -9.1            |
| 2014/12/10 | -5                   | 2014/12/27 | -4.5                 | 2015/1/13  | -7.7                 | -9.7            |
| 2014/12/11 | -11.1                | 2014/12/28 | -2.9                 | 2015/1/14  | -4.1                 | -7.3            |
| 2014/12/12 | -10.6                | 2014/12/29 | -4.5                 | 2015/1/15  | -3.4                 | -5.5            |
| 2014/12/13 | -13                  | 2014/12/30 | -6.8                 | 2015/1/16  | -8                   | -5.9            |
| 2014/12/14 | -11.2                | 2014/12/31 | -10.4                | 2015/1/17  | -11.6                | -10.9           |
| 2014/12/15 | -9.3                 | 2015/1/1   | -14.2                | 2015/1/18  | -7.2                 | -8.9            |
| 2014/12/16 | -14.6                | 2015/1/2   | -12.3                | 2015/1/19  | -8.2                 | -9              |
| 2014/12/17 | -17                  | 2015/1/3   | -7.9                 | -9.5       |                      |                 |

The numerical simulation results of the upper and reservoir are shown in figure 1, and those of the lower reservoir are shown in figure 2.

It can be seen from the numerical simulation results that there is no ice cover in the whole calculation period in the area near the water inlet / outlet, and the ice cover thickness in the southern area far away from the water inlet and outlet in the reservoir area changes from thin to thick, increasing day by day, and the growth rate of ice thickness changes from fast to slow, and it has been generally stable in the later period of calculation. The above simulation results are basically consistent with the prototype observation results.

4. Conclusions

The conclusions are as follows:
Based on the theory of ice hydrodynamics and the MFC module of Visual C++ 6.0, the mathematical model of reservoir ice regime of pumped storage power station in the form of dialog box is established.

The program regards the calculation domain as a plane two-dimensional average water depth flow field for simulation. It initially has an interactive dialog interface of human-computer interaction, and has the function of graphically displaying the simulation results of ice thickness in the reservoir area.

Figure 1. Results of the 40th day simulated ice thickness of the upper reservoir of Pushihe pumped storage power station
The model has been applied to the upper and lower reservoirs of Pushihe pumped storage power station and Hohhot pumped storage power station. The results of the ice regime model are basically consistent with those of the prototype monitoring.

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