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Research Article

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Research on Elimination Technology of Compressed Air Columns in Coal Mine Pumped Storage Underground Reservoir

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Abstract In order to effectively solve the problem of compressed air accumulation in coal mine pumped-storage underground reservoirs, increase ventilation safety, and reduce reservoir capacity loss, combined with specific engineering cases, a corresponding numerical model is established and simulation plans are made. The simulation results show that without additional ventilation measures, the air in the underground reservoir will accumulate and compress in the tunnel, and the final compressed air column volume is about 860m3; under the condition of additional ventilation measures, the air column will The air column in the underground reservoir is basically exhausted when the water is discharged smoothly through the vent hole and the water discharge time reaches 10 minutes, which verifies the effectiveness of the additional ventilation measures. Furthermore, two technical solutions for eliminating compressed air columns, including ground construction vent holes and downhole additional vent pipes, are proposed, and the two technical solutions are compared and optimized. It is believed that the additional vent pipe solution is more environmentally friendly, faster and more convenient. Aiming at the "water resistance" problem caused by the addition of a vent pipe in the mine, the idea of an automatic drainer and the laying of the vent pipe are used to design an air column elimination device for pumped storage underground reservoirs in coal mines. The ball and other core components. Combining the relevant calculation formulas of fluid mechanics, considering factors such as roadway section size, installation difficulty and other factors, determine the technical parameters such as the diameter of the vent pipe and the size of the float. Industrial experiments were carried out in the first phase of the Xinhe Coal Mine Pumped Storage Power Generation Project. The technical solution of ground construction vents was the first choice, which solved the problem of low efficiency of pumped storage power generation, thereby improving the resource utilization efficiency of abandoned mines. As a good alternative, the compressed air column elimination device of pumped storage underground reservoirs in coal mines also provides important design ideas and reference basis for similar engineering cases.

Keywords abandoned coal mine; pumped storage; underground reservoir; compressed air column

1. Introduction

After President Xi Jinping's "double carbon goal" was proposed, China's energy structure change has further accelerated, with solar and other clean energy structures accounting for an increasing proportion [1]. However, solar, wind and other clean energy are affected by seasonal and climatic factors, and their power generation is unstable and intermittent [2]. In addition, with the accelerated pace of national energy restructuring, the product form of coal production as the main industry needs to be adjusted urgently. It is expected that China's coal demand will be less than 1/6 of the current production in 2050 [3], and a large number of mines will take the disposal measures of closing and idling in the future. These abandoned/idle mines will cause numerous dangerous accidents [4] and damage the geological and ecological environment around the mines.

In response to the above two problems, Xie Heping [5,6] and Guo Pingye [7] have studied the use of energy storage in abandoned/idle mines. The process of storing energy through a medium or device and releasing it when needed, energy storage technology is a strategic emerging industry that addresses large-scale access to renewable energy and improves the efficiency of conventional power systems and regional energy systems [8]. According to CNESA statistics [9], by the end of 2020, the cumulative installed capacity of energy storage projects in operation worldwide reached 191.1GW, of which pumped storage has the largest cumulative installed capacity, accounting for 90.3%. Bian Zhengfu [10] and He Tao [11] have explored the problems that may arise during the utilisation of pumped storage in abandoned mines, and some experts have studied the feasibility, theory and technical framework of pumped storage in abandoned mines [12,13,14]. Cao Fei et al. conducted a study on the benefits of building pumped storage power plants in abandoned mines [15], and according to statistics, by the end of 2020, at 50% of the new abandoned mine capacity developed and utilised for large-scale physical energy storage, the theoretical installed storage capacity of 960 million kW can be developed without damaging the environment, and the stored electricity will reach 6.72 billion kWh, and the new investment market will be about 6.7 trillion RMB, which will reach 60% of the active development target of wind power and photovoltaic installation in 2030, in other words, abandoned mines provide underground space resources for pumped energy storage and can indirectly promote renewable energy to meet development needs [16].

Due to the complex structure of abandoned mine tunnels, the ventilation system of underground reservoirs usually needs to be modified and designed in order to ensure gas exchange in the water storage space and to avoid the formation of air resistance. One of the technical problems that needs to be solved is how to discharge the compressed air column from the underground tunnels. According to the law of conservation of energy and the principle of the continuum, compressed air columns appear because the abandoned mine tunnels are located in different strata, there are many low-lying locations, when the water level reaches a certain elevation, due to the height difference in the terrain, some of the tunnels are easily blocked by water and cannot escape. Later, in the process of continuous water release, as the water level rises, a column of compressed air will inevitably be formed, resulting in a reduction in the volume of water stored in the underground reservoir, which in turn leads to a reduction in the efficiency of pumped storage energy generation, At the same time, there is a risk of gas accumulation, which can easily form a large safety hazard. In response to the above problems, there is a lack of relevant engineering practice and specific scheme design at home and abroad, which to a certain extent restricts the development of underground space resource reuse in abandoned coal mines.

In order to effectively solve the problem of compressed air accumulation in underground reservoirs for pumped storage in abandoned mines, the author simulates and analyses the formation process and evolution law of compressed air columns in underground reservoirs for pumped storage in Xinhe Coal Mine according to the specific engineering case of Xinhe Coal Mine of the Coking Coal Group, conducts technical comparison between the two options of proposing ground construction ventilation holes and underground laying ventilation pipes, and optimises the design of the ventilation pipe scheme and proposes a targeted technical solution for air column elimination in order to improve the ventilation system of underground reservoirs in abandoned mines, improve the controllability of water flow in the process of water circulation in underground reservoirs and the efficiency of utilising pumped storage power stations in abandoned mines.

2. Project Overview

Coking Coal Group Baiyun Coal Company Limited intends to use the mine production and living service facilities of the abandoned Xinhe coal mine to renovate and utilize the construction of a pumped storage power station. The above-ground coal storage yard and the surrounding idle square will be used to build an above-ground reservoir, the underground horizontal mine shaft will be used to build an underground reservoir, the central substation and central pump room will be used to build a pump room and turbine room, the main shaft and ventilation shaft will be used as water return and air discharge channels, the above-ground substation will be transformed into a power receiving and outward transmission channel, and other ancillary production facilities, will be utilized to form a damless pumped storage power station. According to the preliminary estimate of the effective water capacity of the total utilization of 100,000 square meters, the total storage capacity of

20MW/150MWh, the initial storage of electricity 3MW/20MWh. the principle of pumped storage in Xinhe coal mine is shown in Figure 1.

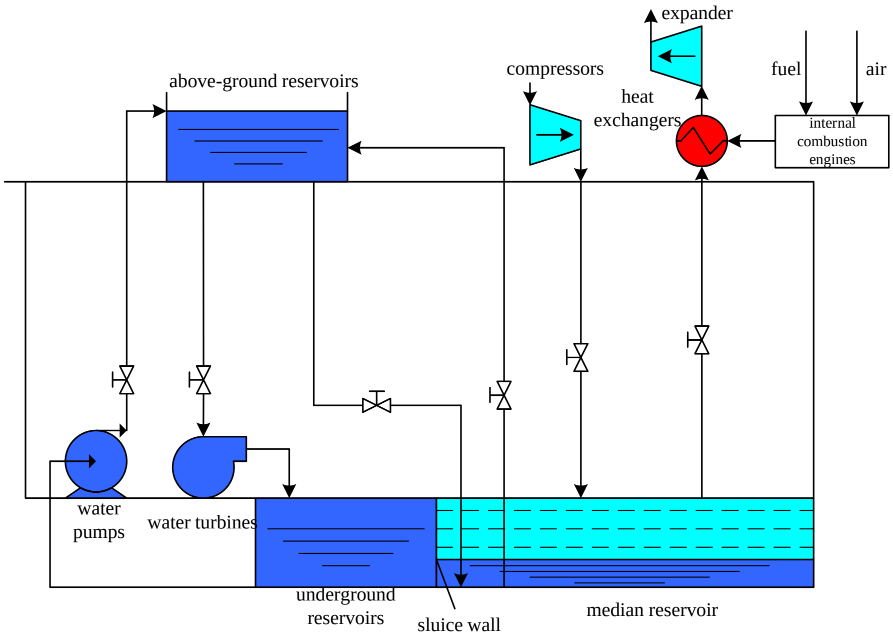

Figure 1: Schematic diagram of the pumped storage principle of Xinhe Coal Mine

In order to ensure smooth gas exchange during the filling and discharging of the water storage space and to avoid the formation of "gas block", it is necessary to optimize the design of the ventilation system for the water storage space. The system should be optimised. The 12091 trackway roof extraction tunnel in the Xinhe coal mine was selected as the object of study. According to the profile parameters of the 12091 trackway top pumping lane and the relative position of the relevant lane, a ventilation pipe is laid in the water storage space to meet the ventilation needs. The inlet of the ventilation pipe should be set in the top part of the roadway of the 12 mining area winch room return wind liaison roadway, along the 12 mining area winch room return wind liaison roadway → 12 mining area return wind up hill → return wind slope roadway → horizontal return wind roadway → waterproof gate → wind shaft bottom, the total length is about 1365 m. The relative position of the ventilation pipe and the roadway is schematically shown in Figure 2.

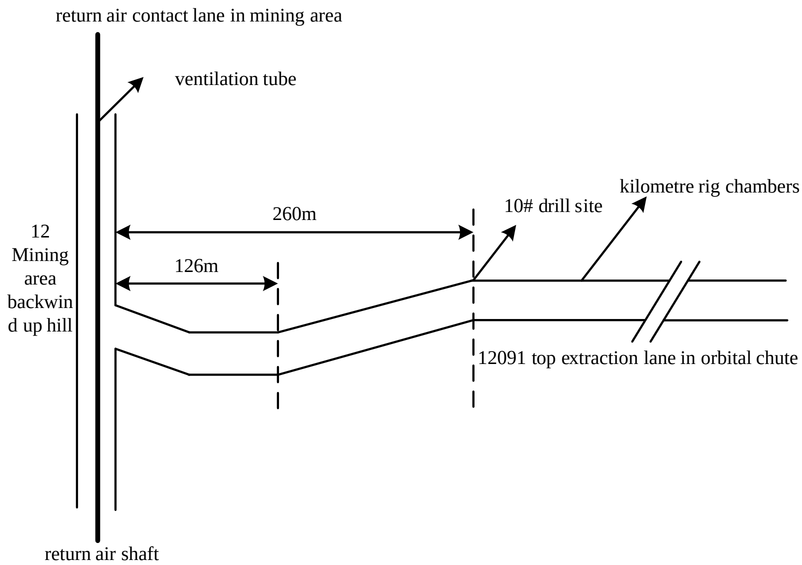

Figure 2: Schematic diagram of the relative position of the snorkel and the roadway

As the lowest point of the bottom plate elevation of the 12091 trackway down-slot top extraction lane is -442m, in the process of filling the underground lane with water, according to the calculation of the gas equation, when the water surface elevation reaches -438m water level, the air in the inner section of the top plate extraction lane on the 12091 surface and the upper section of the top extraction lane in the cuttings will be blocked by water and cannot escape. In summary, according to the plan of laying one ventilation pipe from the return air contact alley of the winch room in the 12 mining area to the bottom of the wind shaft, the ventilation and air exchange system of the water storage space is simple and reliable, but it will lead to the formation of a compressed air column in the inner section of the top extraction alley of the 12091 trackway and the upper section of the top extraction alley of the cuttings.

3. Numerical analysis of the air column formation process

3.1 Numerical model and simulation setup

1) Geometric modelling

In order to study the formation process and evolution law of the compressed air column in the pumped storage underground reservoir of Xinhe coal mine, a geometric model as shown in Figure 3 was established based on track 120911 combined with the arrangement of coal seam gas extraction boreholes on site.

According to the specific engineering reality, the model is simplified for the underground reservoir, the lowest elevation of the reservoir is -504m, the height difference of the 12091 track chute top extraction lane is 18m, the transverse length along the lane profile is set to 500m, the size of the 12 mining area return wind up hill and 12091 track chute top extraction lane are set to 10m x 10m. The dashed position is the ventilation hole to solve the problem of compressed air column formation.

2) Meshing

The 3D model was meshed using the pre-processor Mesh built into Fluid Flow (Fluent) in ANSYS 19.2 and an unstructured mesh was chosen. The quality of the local mesh will determine the reliability of the simulation results, so the mesh was refined at two locations: the wellhead location and the vent opening location. A total of 17,492 meshes were divided into the model, with a mesh quality of approximately 0.85.

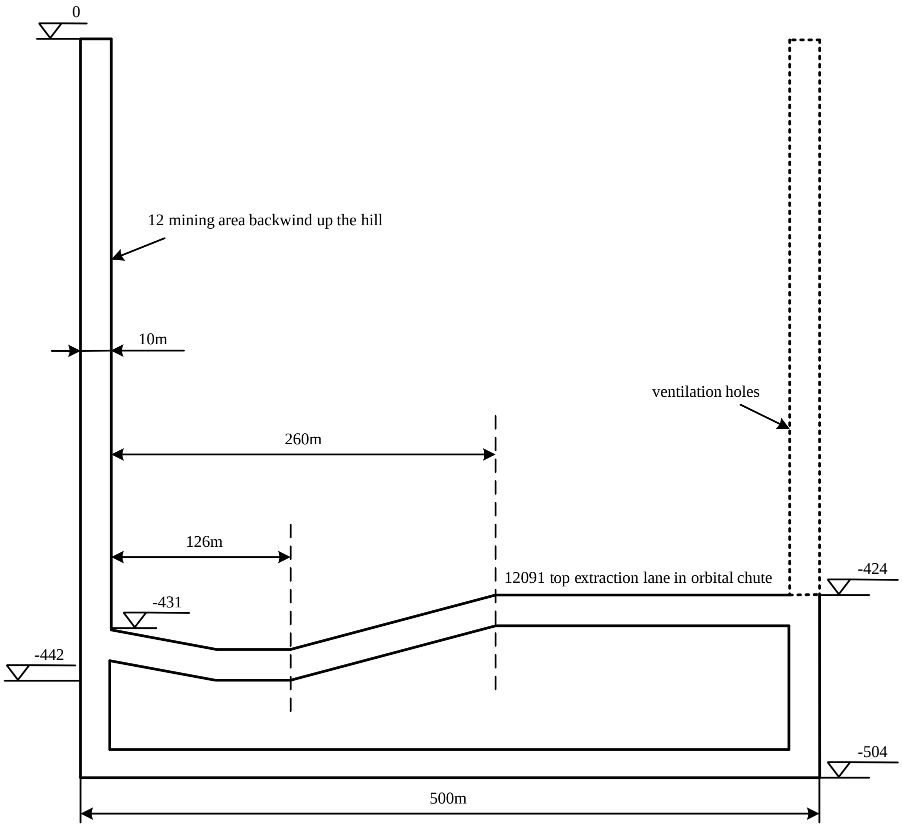

Figure 3: Geometric model of pumped-storage underground reservoir in Xinhe Coal Mine

3) Initial boundary conditions

The k-ε turbulence model was chosen to satisfy the three controlling equations of fluid mechanics and the set of flow equations consisting of turbulent component transport equations without chemical reactions, which satisfy the physical situation to be modelled. The flow rate is 1.5 m/s when the water is released, based on the specific conditions, using the pumping flow rate and the wellhead size, with the wellhead positioned as the inlet and the vent positioned as the pressure outlet.

3.2 Analysis and discussion of results

In order to study the formation process of the compressed air column in the pumped storage underground reservoir of the Xinhe coal mine and the effect before and after the additional venting measures, two working conditions were set up for simulation and calculation analysis without additional venting measures and with additional venting measures respectively, and the compressed air column distribution clouds under the two different working conditions are shown in Figure 4 and Figure 5.

According to Figure 4, without additional ventilation measures, the air in the underground reservoir will accumulate in the lane section and the air column will be compressed as the water level in the reservoir rises and as time passes. The compressed air column is distributed in the inner section of the top extraction lane of the track chute and the upper section of the top extraction lane of the cuttings. When the water surface elevation reaches -320m after the water storage space is completely stored, the hydrostatic pressure formed between the winch room return wind liaison alley (elevation -320m) and the compressed air column (elevation -424m) in the section of the orbital chute top pumping alley is about 1.05 MPa. Under the joint action of atmospheric pressure, according to the gas equation $P_1V_1/T_1 = P_2V_2/ T_2$, ignoring the temperature change due to air compression in the downhole water seal environment can be obtained $T_1 \approx T_2$, then there is $P_1V_1 = P_2V_2$, the final volume of the compressed air column is about 860m^3, which directly leads to a reduction in the volume of the water storage space by 860m^3.

According to Figure 5, under the condition of additional ventilation measures, the air column will be discharged smoothly through the ventilation holes. When the water release time reaches 10min, the air column in the underground reservoir is basically discharged. Considering that there should not be excess water in the vent hole, a blocking valve needs to be installed at the lower end of the vent hole, which can be opened to prevent water from overflowing after the air column has been successfully discharged.

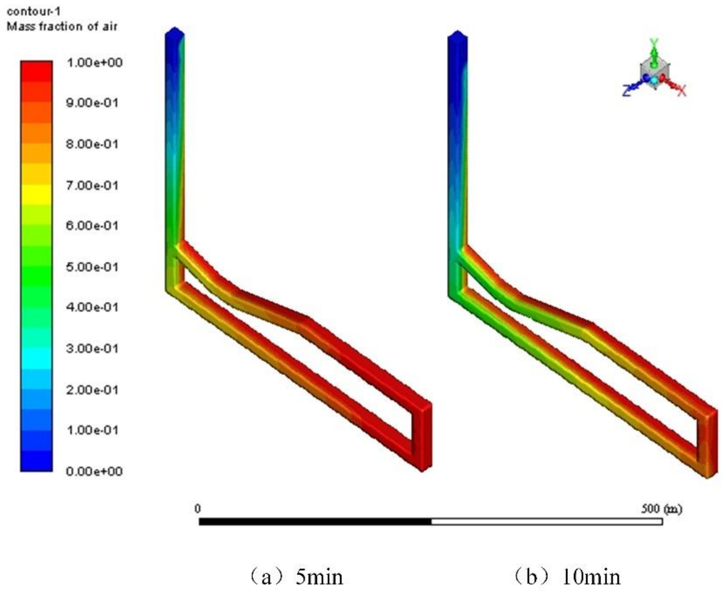

Figure 4: Without additional ventilation measures, the compressed air column distribution cloud map

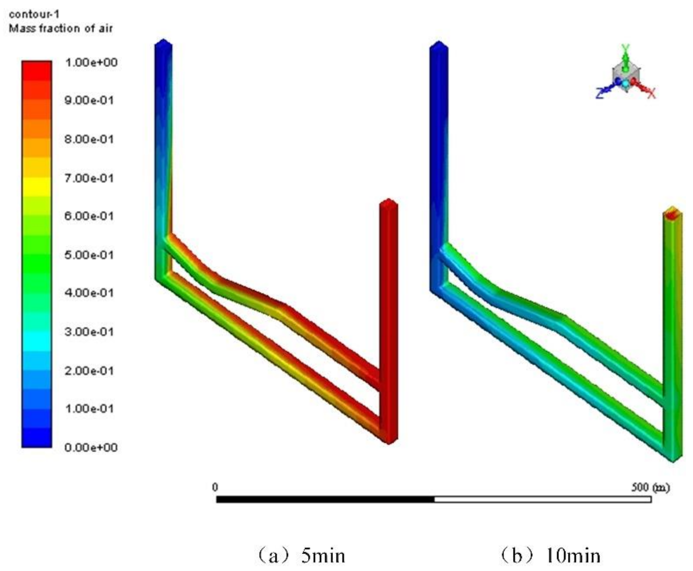

Figure 5: Cloud diagram of compressed air column distribution under additional ventilation measures

4. Preferred air column elimination technology

For the problem of pumped storage compressed air columns in coal mines, two technical solutions are provided as shown in Figure 6. The first solution is to export the air by drilling ventilation holes 2 at the surface to the compressed air column of the roadway 1; the other is to export the air by laying air pipes 3 to the compressed air column of the roadway 1 through the return air contact lane 4 in the mining area.

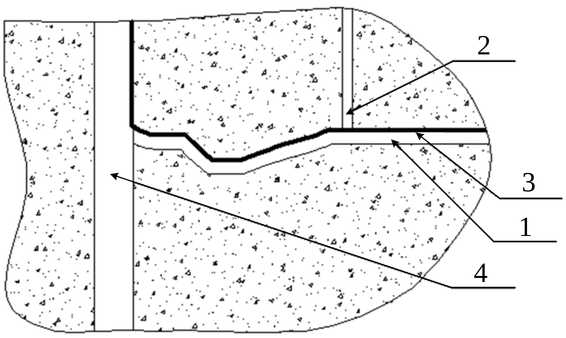

Figure 6: Schematic diagram of two technical solutions

4.1 Construction of ventilation holes in the ground

The problem of compressed air accumulation in the water storage space is solved by constructing ventilation boreholes (breathing holes) at ground level. Usually, there is only a margin of about 4m in relation to the relative position of the ventilation hole and the roadway, and the hole slope should be strictly controlled, requiring the hole to be vertical as far as possible. Simple hydrological observation should be done carefully, and if any abnormalities are encountered during drilling, the starting and ending depths should be accurately recorded, and the whole hole should be plugged whenever there is a leak. Hole depth check: Every 100m of drilling and the final hole should be checked for hole depth. Hole skew measurement: 1 skew measurement every 200m to understand the degree of hole skew. The hole must be measured near 340m deep and communication with the mine must be strengthened to ensure mine production safety. Electrical logging must be carried out before the pipe is lowered to determine the coordinates of the drill hole drop bottom and to provide data for finding the location of the drill hole downhole. A pressure resistance test of not less than 10MPa must be done on the casing after the final hole is drilled.

In summary, ventilation holes generally need to be drilled to 600-1000m underground, and the construction is difficult, for the drilling depth alone, it will consume a lot of human, material and financial resources, the project volume is huge; due to the different underground geology, hardness varies, but also comprehensive air column location, geological conditions and other factors to choose the ventilation hole path, and will add difficulty to the drilling work; in addition, there is also the problem of large budget expenditure, because In addition, there was also the problem of large budgetary expenditure, as it involved the demolition and relocation of houses and noise nuisance, the budget also needed to take into account the cost of demolishing the houses of villagers in Xiaopo village and the coordination of industrial and agricultural relations during construction. In addition, as the water storage space needs to be ventilated and ventilated every day, it is impossible to solve the problem of noise nuisance that will persist after commissioning.

4.2 Additional ventilation pipes down the shaft

If only one ventilation pipe is laid in the return wind up the hill road (main road), the water storage space ventilation and air exchange system is simple and reliable, but the problem of reduced storage space capacity due to the formation of compressed air columns has not been solved. Therefore, it is not possible to follow the traditional laying idea and additional ventilation pipes need to be considered at the location of the track chute (where there is a height difference). With the addition of a ventilation pipe, there will be no compressed air column during the first filling, but at the same time the air pipe will also be filled with water when the mine is filled with water, after which the water in the mine will be pumped to the upper reservoir, the air pipe will retain water, and during the second filling, the water retained in the ventilation pipe will form a "water block", which will cause the formation of a compressed air column again. In order to solve this key problem, an automatic water release device was designed to eliminate the air column in underground reservoirs in abandoned mines, using the idea of an automatic water release device in low-lying areas of the roadway, in conjunction with the laying of ventilation pipes.

5. Design of the air column elimination device

5.1 Structural components

In order to effectively solve the problem of compressed air accumulation in underground reservoirs of abandoned mine pumped storage, increase ventilation safety and security and reduce reservoir capacity losses, a coal mine pumped storage compressed air column elimination device was designed, as shown in Figure 7. The device consists of the following components: a tee fitting with three ports, a hollow annular spherical housing directly below one port, the large end of the housing sealed by a mesh tray, and a float set within the housing.

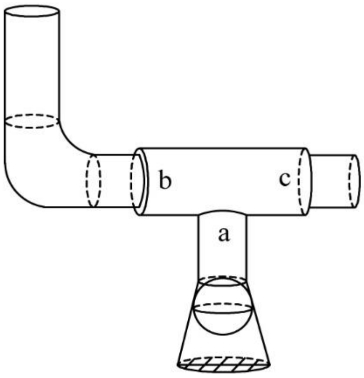

Figure 7: Schematic diagram of the structure of the air column elimination device

Wherein the tee fitting has three ports a, b and c. The b and c ports are each connected to a vent pipe, the a port is the vertical downward port of the tee fitting, and a hollow annular spherical shell is provided directly below the a port (as shown in Figure 8), the small end of the shell is sealed to the a port and the large end of the shell is sealed by a mesh tray. The housing is provided with a floating ball, the outer diameter of which is greater than the inner diameter of the a-port, and which by buoyancy will form a line seal with the inner wall of the housing or the a-port. The small end of the housing is sealed to the a-port by a threaded fit. To increase the sensitivity of the float preferably a hollow float, the inner surface of the housing is provided with a silicone coating to prevent damage to the housing from foreign objects. A silicone seal is provided on the inner surface of the housing or at the a-port to increase the air tightness.

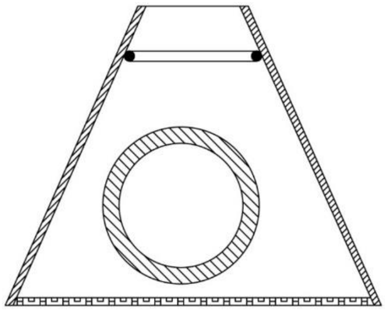

Figure 8: Schematic diagram of shell component structure

In practical applications, the relevant physical parameters such as the diameter of the vent pipe and the flow rate of the fluid in the pipe need to be determined. According to the formula for head loss of fluid flow in a circular pipe, the corresponding along-travel and local losses can be calculated, and combined with the highest energy consumption requirements in the pumped storage power generation process, the total head loss should be no greater than the critical value A. The specific calculation formula is as follows.

$$h_f = \lambda \frac{l}{d} \frac{v^2}{2g} \quad (1)$$

$$h_j = \zeta \frac{v^2}{2g} \quad (2)$$

$$h = h_f + h_j \le A \quad (3)$$

Where,

h_f—Along-track head loss, m;

h_j—Local head loss, m;

h—Total head loss, m;

l—Flow section length, m;

d—Ventilation tube diameter, m;

v—Cross-sectional average flow rate, m/s;

λ—Along-travel resistance factor;

ξ—Local resistance factor;

A—Total head loss max, m, determined by specific project requirements.

Another set of relationships can be determined from the relationship between flow rate and flow velocity and cross-sectional area.

$$Q = v \frac{\pi d^2}{4} \quad (4)$$

Where ,

Q—Fluid flow rate in the vent pipe, m^3/h.

The fluid flow rate in the ventilation pipe can be determined according to the engineering design, and the corresponding ventilation pipe diameter and section average flow rate can be obtained by combining two sets of equations. The ventilation pipe should be combined with the size of the tunnel section to increase the diameter of the pipe as much as possible to reduce wind resistance and energy loss.

The diameter of the tee pipe should be matched with the diameter of the ventilation pipe; the diameter of the tee branch pipe should be selected according to the project requirements, taking into account the size of the roadway section, the ease of installation and other factors.

The size of the inner and outer diameters of the hollow float and the size of the shell tension angle are determined according to the buoyancy of the float, the pressure of the air column, the gravity of the float and the cross-sectional area of the branch pipe, etc. The shell tension angle is recommended to be around 30°. Ensure that the hollow float can be sealed quickly and effectively during the filling process and can fall into the tray effectively after pumping. A force analysis of the float after it has been floated should satisfy the following conditions.

$$\rho gV \geq mg + p_0 S + f \quad (5)$$

Where,

ρ—Density of water, 1g/cm³;

g—Gravitational acceleration, taken as 9.8m/s²;

V—Volume of hollow floating ball submerged in water, m³;

m—Float mass, kg;

p_0—Air column pressure, taken as 0.1 Mpa;

S—Cross-sectional area of branch pipe at lower end of tee fitting, m²;

f—Downward component of friction between housing and hollow float, N.

5.2 Implementation method

After each component is assembled, the high pressure water flow can be manipulated to test the seal of each component connection to ensure a good seal, and only after the test is passed, can it be put into use. The tee fitting is located at the lowest point of the vent pipe, the port where the tee fitting is connected to the housing is the lowest port and is located in the vertical direction, the housing, float and mesh tray are located directly below the port. The flow of the specific implementation method is shown in Figure 9.

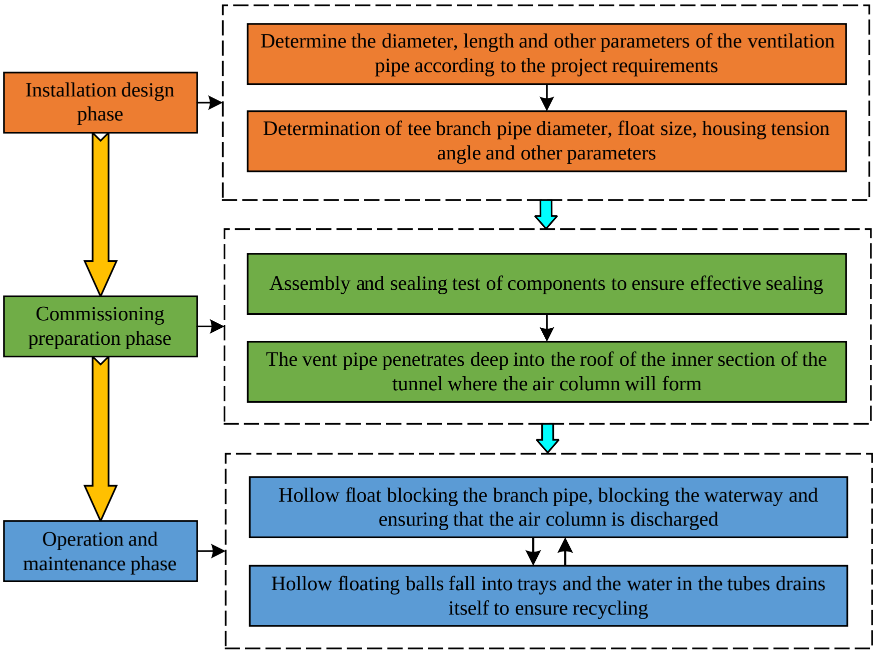

Figure 9: The specific implementation method process is shown in the figure

In the formal operation stage, when filling the underground reservoir, the water level reaches a certain elevation, the hollow floating ball floats up with the buoyancy provided by the water pressure to ensure that the air column is discharged through the pre-set ventilation tube until the tube is full of water and the air column in the storage space is eliminated. When the water level of the underground reservoir is lower than the inlet elevation of the vent pipe, the water in the pipe will cause the hollow float to fall into the tray under gravity, and the water formed in the vent pipe at the low-lying part of the laying will be emptied automatically, in order to solve the impact of the water block formed in the low-lying part of the vent pipe on the re-filling of the water, and to ensure that when the underground reservoir is filled with water again The air column can again be successfully removed.

6. Conclusion

(1) To address the formation process and evolution law of the compressed air column in the underground reservoir of coal mine pumped storage, the corresponding numerical model is established and simulated with specific engineering cases. Under the condition of no additional ventilation measures, the air in the underground reservoir will accumulate and compress in the tunnel section, and the final volume of the compressed air column is about 860m3; under the condition of additional ventilation measures, the air column will be discharged smoothly through the ventilation holes, and the air column in the underground reservoir is basically discharged when the water release time reaches 10min. The effectiveness of the additional ventilation measures was verified through simulation.

(2) Two technical options are proposed: the construction of ventilation holes on the surface and the installation of additional ventilation pipes downhole. However, the construction of a ventilation hole on the ground near the mine site usually involves a long construction period, high budget, house demolition and noise disturbance; if the installation of an additional ventilation pipe is considered to lead the air column out, after filling with water, water will remain in the ventilation pipe and accumulate in the low-lying areas of the pipe to form a water block, and the compressed air and the difference in water level when filling again will not be able to lift the water out, which will lead to a secondary The air column cannot be removed smoothly again when used.

(3) To address the problem of "water blockage" caused by the installation of additional ventilation pipes downhole, an automatic water release device is designed to eliminate the air column in underground water reservoirs of coal mine pumped storage by adopting the idea of automatic water release device and matching the laying of ventilation pipes. The specific operation process includes three stages: device design, commissioning preparation and operation and maintenance, through scientific calculations to ensure that the relevant technical parameters involved in the device are reasonable. At the same time, the construction of ventilation holes is significantly reduced, saving engineering expenditure.

(4) In the first phase of the Xinhe coal mine pumped storage power generation project, the technical solution of ground construction of ventilation holes was preferred to effectively solve the problem of compressed air accumulation in the underground reservoirs of abandoned mine pumped storage, with remarkable results. However, the installation of additional ventilation pipes with automatic water release devices as a good alternative can still provide important design ideas and reference basis for similar engineering cases.

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