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Research on Sampling Device of High Pressure and Low Temperature Preparation Kettle

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Abstract

Natural gas hydrate (NGH) has been regarded as an alternative energy source for traditional fossil energy such as coal and petroleum. It has abundant reserves in the world, but it is difficult to develop. The marine non-diagenetic gas hydrate solid-state fluidized mining laboratory independently researched, designed, constructed and constructed by Chinese scientific research units will become an important equipment for scientific research on marine non-diagenetic NGH development. The core equipment of the laboratory is the NGH preparation kettle system simulating the seabed high pressure and low temperature state. In order to monitor whether the NGH sample generated in the preparation kettle meets the test conditions of the simulated mining technology, it is necessary to take the NGH sample from the preparation kettle according to the process requirements, so the research on the sampling device of high pressure and the low temperature preparation kettle has become a top priority. Based on extensive research, this paper proposes an NGH sampling device based on magnetic coupling drive and electronically controlled drive fusion based on the concept of organic combination of electromechanical instruments. According to the actual parameters of the NGH preparation kettle, the design technical indicators of the sampling device were determined. The overall scheme design, hardware structure design, software programming and simulation of the device were completed. The SolidWorks design, machining and device selection of the drive, connection and sampling head structure were completed. Type and analysis, assembly and commissioning work; control circuit design, Smith predictive compensation fuzzy PID control algorithm for pressure, pressure regulation and pressure relief control of the pressure inside the sampling pressure tube, and simulation experiments were carried out by MATLAB software.

Through the indoor simulation experiment of the principal machine of the sampling device, it is verified that the research result of the paper is correct, the structure is reasonable, and it has certain innovation and practicability, which provide technical support for the practical NGH sampler in the future.

Keywords

Natural gas hydrate (NGH); reparation kettle; Sampling device.

1. Introduction

Natural Gas hydrates (NGH), are ice-like crystalline materials formed by Natural Gas (mainly methane) and water at high pressure and low temperature. They are usually distributed in deep-sea sediments or permafrost on land Because of its appearance like ice and will be burning in case of fire, so is called "flammable ice" (Combustible ice). NGH is mostly white or light gray crystal, and its combustion pollution is far lower than traditional fossil energy (such as coal, oil, etc.), and it is widely distributed in the world. Scientists estimate that its reserves could last

1,000 years, and countries see it as an alternative to conventional fossil fuels. At present, more than 30 countries and regions in the world are studying and investigating natural gas hydrates. However, due to the great difficulty in development, safety problems such as geological risks, environmental risks and production equipment have not been fundamentally solved, so the commercial exploitation technology of all countries in the world is at the stage of in-depth scientific exploration.

How to develop Marine nondiagnostic gas hydrates efficiently and safely has become a hot research target in the world. Zhou Shouwei, academician (academician of the Chinese Academy of Engineering, chief technical adviser of China National Offshore Oil Corporation and director of the State Key Laboratory of Oil and Gas Reservoir Geology and Development engineering), proposed the solid fluidization mining model of Marine non-diagenetic gas hydrate, which is expected to solve the world's difficult problem. The laboratory is jointly built by Chinese scientific research institutions (Southwest Petroleum University, China National Offshore Oil Corporation and Honghua Group), and is completely developed, designed and built by China independently (As shown in Figure 1-2), Completed in early 2018, it will become an important equipment for scientific research on Marine non-diagenetic NGH development. The establishment of this laboratory will attract experts and scholars from all over the world to jointly experiment, explore, test and analyze, and study the development mechanism, etc., provide theoretical and technical support for the commercial exploitation of human non-diagenetic NGH, and lead the global research and development direction of Marine non-diagenetic NGH.

2. The overall scheme design of the sampling device for the preparation kettle

2.1. Analysis of system design requirements

This design is aimed at the sampling of non-diagenetic NGH in NGH preparation kettle. It is necessary to understand the formation condition and preparation process of NGH.

The formation conditions of NGH can be summarized as provenance conditions and temperature and pressure conditions. The provenance condition refers to the need for large amounts of natural gas (mainly methane gas) and water, which are the main components of combustible ice and the material basis of formation. Environmental conditions require low temperature and high pressure. Generally speaking, they require a pressure lower than 10 ℃ and greater than 10 MPa (about 1000 meters below water depth). Only under such a special environment can water solution containing a large amount of natural gas crystallize to form combustible ice. In addition, favorable storage space is needed.

In essence, the formation process of gas hydrate is a process of equilibrium change of hydrate, solution and gas, all the factors that may affect the phase balance will promote the generation or decomposition of hydrate. For example, when temperature increases or pressure decreases, hydrate will naturally decompose into natural gas and water, which is the process of changing from solid phase to gas and liquid phase. On the contrary, when the temperature is lowered or the pressure is increased, natural gas and water can form hydrates. Now researchers have obtained the equilibrium temperature and pressure curve of hydrate stability through many experimental data. Gas hydrate in preparation according to balance the pressure curve, find the suitable temperature pressure value, by creating artificial reservoir environment, will be made of hydration, gas and water and hydrate in sediment, broken through the mixer, stir constantly make gas hydrate slurry, thus human form like the deep shallow consolidation state of diagenetic NGH samples.

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2.1.1. Design indexes and principles of system devices

The design of the sampling device for the high-pressure and low-temperature preparation reactor must conform to the construction environment and test operation flow of the solid fluidization production laboratory of the Marine nondiagnostic gas hydrate. According to the construction environment of the laboratory and the structure of the natural gas hydrate preparation kettle, the design indexes of sampling device for the preparation kettle are shown in Table 2-1:

Table 2-1 Design indicators of sampling device for the preparation kettle

Working pressure of sampling pressure pipe (MPa)	10
Temperature T (°C)	- 10 - 50 +
Valve size (mm)	< 50
Sample volume (Cm3)	> 15
Inlet depth	450

Based on the working environment of the preparation kettle sampler, in the structural design and the selection of working mode, good performance must be satisfied under the condition of ensuring safety. The design principles are as follows:

Safety: The process of pressurizing and reducing pressure of pressure pipe through natural gas is involved in the experiment, so the sealing of pressure pipe and the safety and reliability of the whole device must be guaranteed.

Applicability: After achieving the objectives of this subject, the device can also be adapted to other similar samples by certain modifications.

Convenience: In the process of experiment and sampling, it is necessary to conveniently dock with the preparation kettle and take and place samples in the sampler.

The sampling device for high pressure and low temperature preparation kettle mainly consists of hardware part and software part, the hardware part includes the structural design of sampling device, sampling head design and control circuit design. The software part includes the design of sampling pressure control algorithm and sampling head motion control. This design controls the pressurization, pressure stabilization and pressure relief process of the sampling pressure bearing tube for the sampling pressure bearing tube. During the pressure stabilization process, the pressure sampling operation is carried out for the gas hydrate in the preparation reactor on the premise of the laboratory test of the solid fluidization mining of the non-diagenetic natural gas hydrate in the whole ocean. The overall scheme design block diagram of the system is shown in Figure 2-2.

2.1.2. Scheme design of mechanical mechanism and control circuit

The design of mechanical structure is composed of two parts: sampling device connection structure design and sampling head design. The connection structure of the sampling device belongs to the main part of the machine and is the guarantee of realizing the function of the whole system. It needs to consider the safety of its work according to the actual working environment, and design its structure according to the transmission mode of power and the function to be realized, considering its practicability and convenience. The design of sampling head needs to define the sampling target according to the actual working state in the preparation kettle. Because the reserved pipe diameter is small, the volume and overall shape design of the whole sampling head should be considered. In order to prepare the slurry NGH sample in the kettle, it is necessary to realize certain tightness.

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The control circuit is the hardware guarantee for the sampling device to realize the target task. It consists of controller, motor, driver, power supply, sensor, special circuit and actuator. Its control circuit design scheme is shown in Figure 2-3:

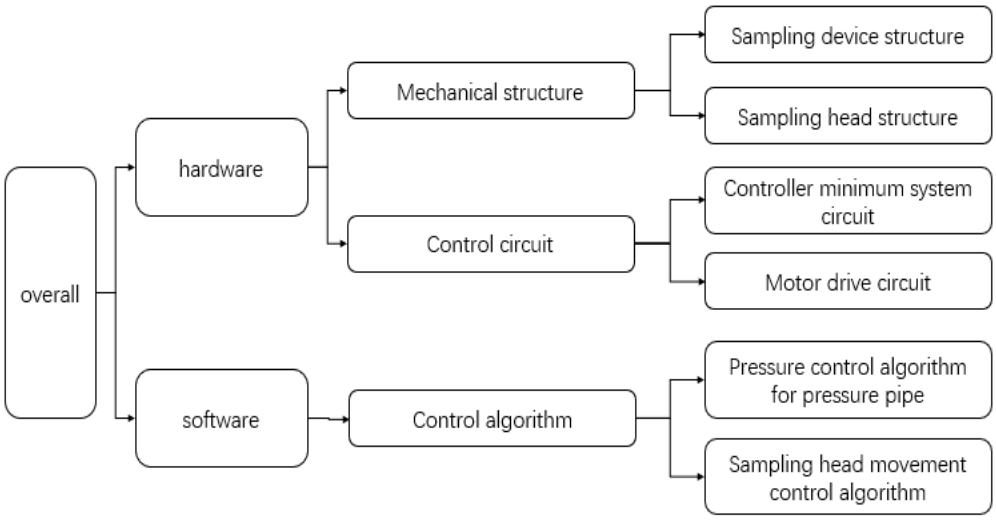

FIG 2-2 Block diagram of overall scheme design of the system

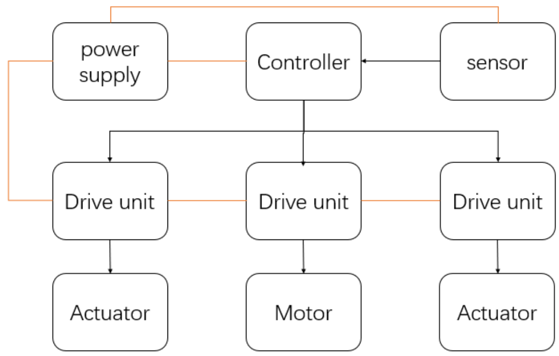

FIG 2-3 control circuit design scheme

The control circuit mainly includes the peripheral circuit of the controller and the drive circuit of the motor and other execution units. The controller can send the control signal to each actuator through the compiler to drive the whole system.

2.2. Hardware design of the sampling device for the preparation kettle

2.2.1. Overall structural design of the sampling device for the preparation kettle

The sampling target of this design is the slurry NGH sample in the Marine nondiagnostic NGH solid fluidization production laboratory NGH synthesis reactor. During the design of the NGH preparation reactor, a 50mm sampling hole was reserved on the side wall 600mm away from the bottom of the reactor and 450mm away from the top of the stirring head to facilitate the sampling in the test. The structural diagram of the NGH preparation reactor is shown in Figure 2-4. The inner diameter of the gas hydration reactor is 900mm, and the center is equipped with an agitator vertically downward from the top of the reactor. The agitator blade is located at the bottom of the reactor with a height of 100mm. During operation, the agitator will keep stirring to ensure that the hydrate is in a fluid slurry.

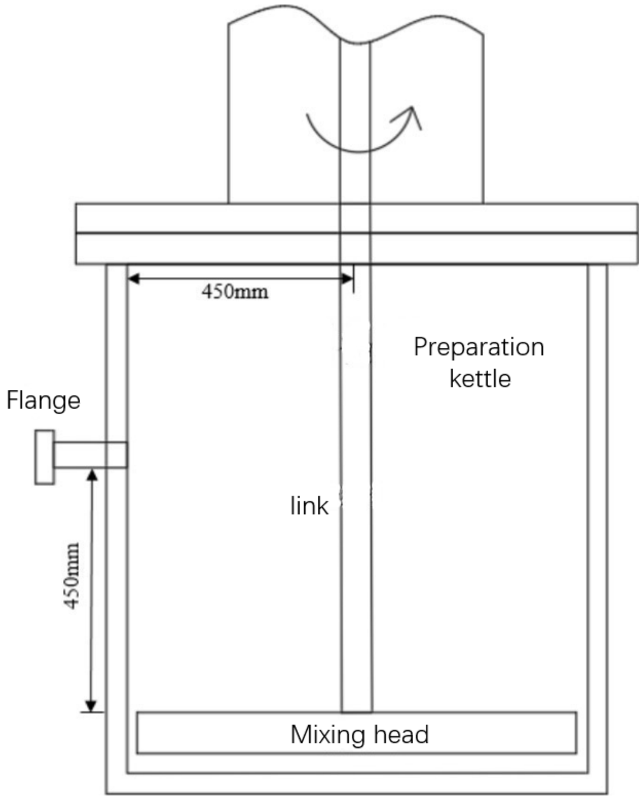

FIG 2-4 Schematic diagram of the reactor for the preparation of NGH

According to the actual structure and working state of the preparation kettle and on the premise that the work of the gas hydrate preparation kettle is not affected, the following sampling device structure for the high-pressure and low-temperature preparation kettle is designed in this paper (as shown in Figure 2-5)

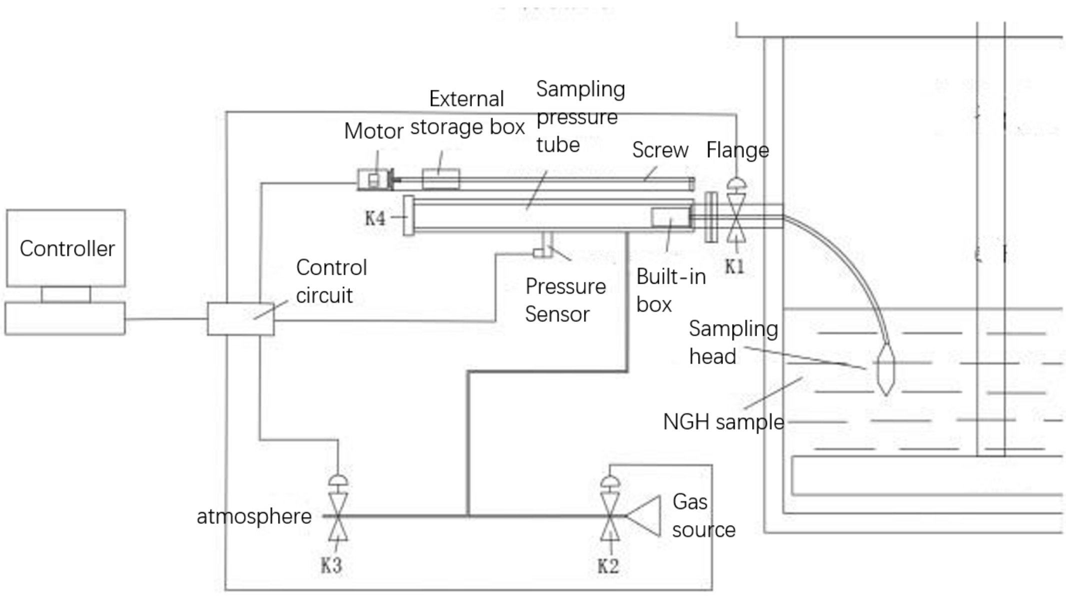

FIG 2-5. Schematic diagram of sampling device for high-pressure and low-temperature preparation kettle

In the figure, K1, K2 and K3 are solenoid valves, K1 controls the connection between the preparation kettle and the sampling pressure pipe, K2 is the air source inlet valve, K3 is the exhaust valve, and K4 is the quick-opening sealing head. The sampling device is externally connected to the preparation kettle, and the working process is as follows:

(1) Place the built-in container, sampling head and its connection part in the sampling pressure tube, close the sealing head K4, start the controller, read the pressure sensor data, and conduct calibration;

(2) After the controller receives the air pressure data in the preparation kettle from the general control system of the laboratory,

Open inlet valve K2 to allow natural gas from the laboratory's total gas source to enter the sampling pressure pipe;

(3) The pressure inside the sampling pressure tube is detected by the pressure sensor. When the target pressure is reached, the controller simultaneously controls the intake valve K2 and exhaust valve K3 for the pressure stabilization control. Then the solenoid valve K1 is opened to connect the sampling pressure tube with the preparation kettle.

(4) The controller starts the motor to run and makes the sampling head enter the preparation kettle for sampling operation;

(5) After the sampling is completed, the controller controls the sampling head back to the sampling pressure tube, and then closes the solenoid valve K1, closes the air inlet valve K2, and keeps the pressure reducing valve K3 open to relieve the pressure of the sampling pressure tube;

(6) After the pressure relief of the sampling pressure pipe is completed, close the pressure relief valve K3 and the whole device work flow is finished.

In addition, considering the safety factor, in order to prevent the sampling pressure pipe due to the large pressure, produce safety accident, personnel life safety threat to experiment, the design for the pressure value sets a limit, when the sampling pressure pipe pressure force is more than 12 map (the lab can simulate water depth is 1200 m), the controller will automatically shut off inlet valve K2, open the discharge valve K3, if K1 in an open position, will make the sample as fast as they head back pressure in the tube and close the K1, ensure pressure pipe sampling and preparation of isolation between the kettle, to ensure the personal security in test personnel.

2.2.2. Selection of sampling device for the preparation kettle

This design uses STM32 microcontroller with high performance, low cost, low power consumption, fast running speed, strong anti-interference ability and ARM32 bit Cortex-M3 as the kernel. STM32 microcontroller is produced by STMicroelectronics (ST) company, and the working frequency can reach 72MHz. Core chip has a variety of commonly used communication interfaces, but also provides 3 ADC (12 bits), 4 general timers (16 bits) and 2 PWM timers and other powerful peripherals. The STM32F103 series is available in four package types, ranging from 48 pins to 100 pins. STM32F103 series single chip microcomputer can complete the work within -40 to +105 degrees Celsius. Depending on the device you choose, the different Settings include peripherals.

This design uses 57BYG250B stepper motor (as shown in Figure 3-5), its parameters and the driver drive the operation of the stepper motor. The stepper motor driver has a stepper motor rotational square input interface, a stepper motor enabling interface, and a subdivision control with up to eight 128 subdivisions and an input voltage of DC9~42V. The controller sends a certain pulse to the driver, and the driver controls the rotation Angle of the stepping motor according to the received pulse frequency. At the same time according to the received pulse frequency to control the stepper motor rotation speed, the final realization of the automatic mover fast and stable motion.

Since the sampling pressure pipe will be directly connected to the preparation kettle and will be in the state of pressure, the material that can withstand high pressure shall be selected for the sampling pressure pipe. At the same time, in order to facilitate the observation of the control movement of the sampling head in the sampling pressure tube, the wall of the sampling

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pressure tube should be as transparent as possible. Therefore, the plexiglass tube is selected in this design. The inner diameter of the tube wall is 74mm and the maximum pressure is 12MPa. The organic glass tube with high transparency, light transmittance over 92%, and it's clear to see inside the movements and changes of the object, and high mechanical strength, tensile impact resistant capability is strong, can bear high pressure and low temperature environment, magnetic can penetrate, apply to the special working environment, and has the very good cutting performance, processing is convenient.

In order to control the gas pressure in the sampling pressure tube, it is necessary to measure the pressure in the sampling pressure tube in real time. As the sampling pressure pipe needs to be controlled according to the pressure in the preparation kettle, and the measuring range of the pressure sensor needs to reach 12MPa, miK-P300 pressure transmitter is selected to measure the transmission pressure.

In order to realize the sampling with pressure and reduce the volume of the sampling pressure tube, the power source is separated from the sampling pressure tube. The magnetic coupling transmission mode is selected, so the magnetic carrier needs to be considered. Because the inner box will be placed in the sampling pressure tube, and there is a certain space gap with the outer box, it is necessary to select the carrier with strong magnetism.

Neodymium magnets, also known as Nd Feb magnets, have a large magnetic energy product and are the most used rare earth magnets. The neodymium magnet used in this design is 40*40*20mm, which is suitable for the pressure tube of sampling. The physical picture of the neodymium magnet.

2.3. Structural design of electrical and magnetic coupling transmission links

2.3.1. Design of lead screw

Due to the coupling of magnetic force to drive, considering the influence of magnetic force on the metal, it is necessary to conduct antimagnetic treatment on the device. The regular standard lead screw is mostly made of steel, which is not suitable for this design. Therefore, an applicable lead screw is designed according to this sampling device. The design structure diagram of the lead screw is shown in Figure 2-6.

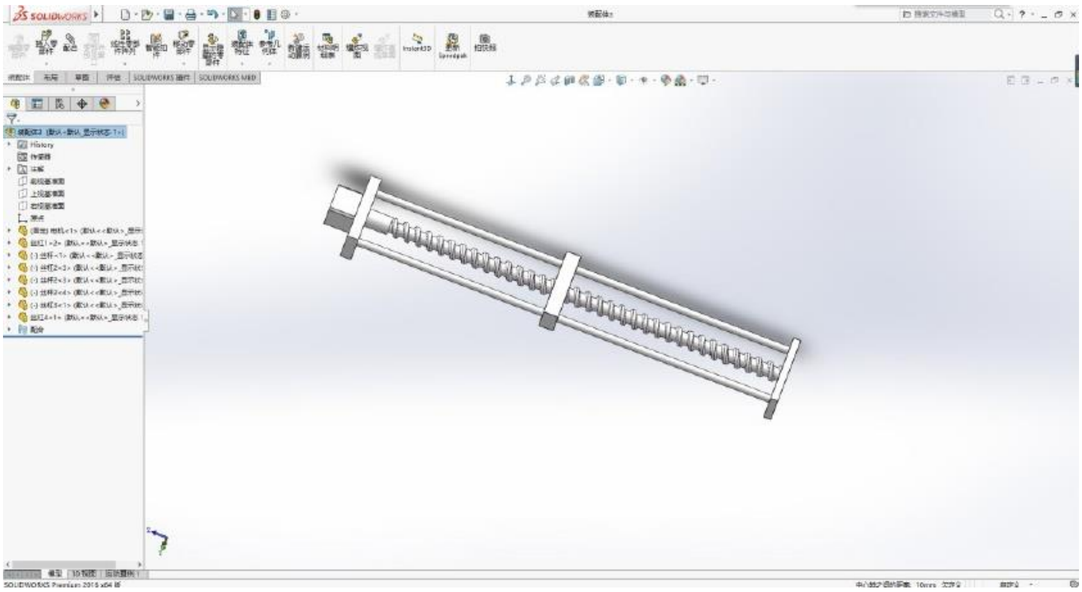

Figure 2-6 Lead screw design structure

The lead rod is made of copper and there are two guide rods made of aluminum on each side. The stroke required by the sampling device is 500mm, so the length of the lead rod is machined to 600mm. In order to minimize the gap between the inner and outer containers and ensure sufficient magnetic force, the outer containers will be suspended directly on the screw rod

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about 2mm from the outer wall of the sampling pressure tube below, without friction generated with the outer diameter of the sampling pressure tube. The guide bar can fix the external object box on the screw rod, avoid the external object box shaking, and ensure its movement direction is the square direction required by the design. Next can be wrapped around the magnet with copper, only in the direction of the need to expose the magnet, the direction of the magnetic induction line concentrated in one direction, to achieve antimagnetic effect.

2.3.2. Pipe connection

According to the structure of the preparation kettle, the sampling head needs to go through a 90-degree turn when entering the preparation kettle to reach the sampling position. According to the structure of the kettle body, the space left for the sampling head in the kettle is about 400mm*450mm on the plane. The rigid structure is used to connect the sampling head, which will make it difficult for the sampling head to carry out steering operation. Therefore, this design chooses to use the flexible connection of flexible pipe with certain stiffness. The use of flexible pipe connection will provide axial push and pull for the sampling head. After the sampling head enters the kettle body, it will naturally turn to fall under the action of gravity and will not contact with the agitator shaft in the center of the kettle body. In addition, the stiffness of the flexible pipe will avoid direct contact of the sampling head with the wall of the kettle and relatively large shocks. Due to the tightness and safety of the sampling pressure tube, the power source of the sampling head is only axial, and the sampling head needs to close the container of the obtained NGH sample in addition to its own sampling movement, so the single flexible pipe connection cannot be realized This action. This design imitates the principle of brake line, adding a flexible rope in the flexible tube to complete the action of closing the sampling container. The schematic diagram of flexible pipe with flexible rope is shown in Figure 2-7.

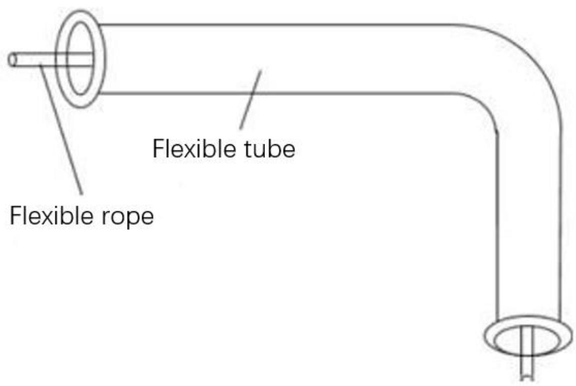

FIG. 2-7 Schematic diagram of flexible pipe with flexible rope

2.3.3. Connection design of built-in box

The built-in case needs to relate to the flexible tube, so the connection device between the built-in case and the flexible tube is designed, as shown in Figure 2-8. A stretch card is placed at the front of the built-in box. The lower end of the elastic card is directly connected with the flexible tube, and the back part has a spring. Under normal conditions, the elastic card is attached to the front end of the magnetic box. When the sampling head reaches the sampling position, the upper part of the elastic card is attached to the pre-designed baffle inside the pressure tube, so that the elastic card moves backward relative to the built-in box and pulls the flexible rope. See Appendix 1 for the design drawing of the built-in box.

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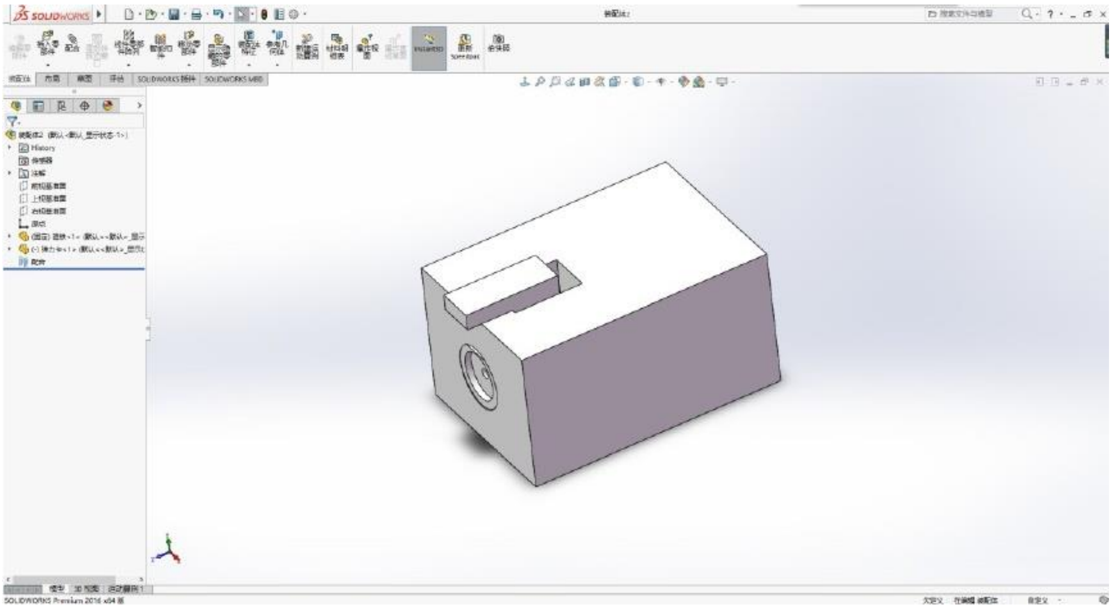

FIG. 2-8 Connection device diagram of built-in box and flexible tube

It should be noted that the inner box will be rounded during the processing of the four sides, to reduce the damage to the inner wall of the sampling pressure tube, and protect the inner wall of the sampling pressure tube to crack and cause the wall to break.

2.3.4. Control circuit design

This design control circuit is based on the single chip microcomputer as the core, the solenoid valve and step motor work together control. Because MCU can only output control signal, there is no driving ability. The solenoid valve control and stepping motor need 24V DC to work, so it needs to cooperate with the corresponding drive circuit and driver to make the device work normally. The control circuit diagram is shown in Figure 2-9.

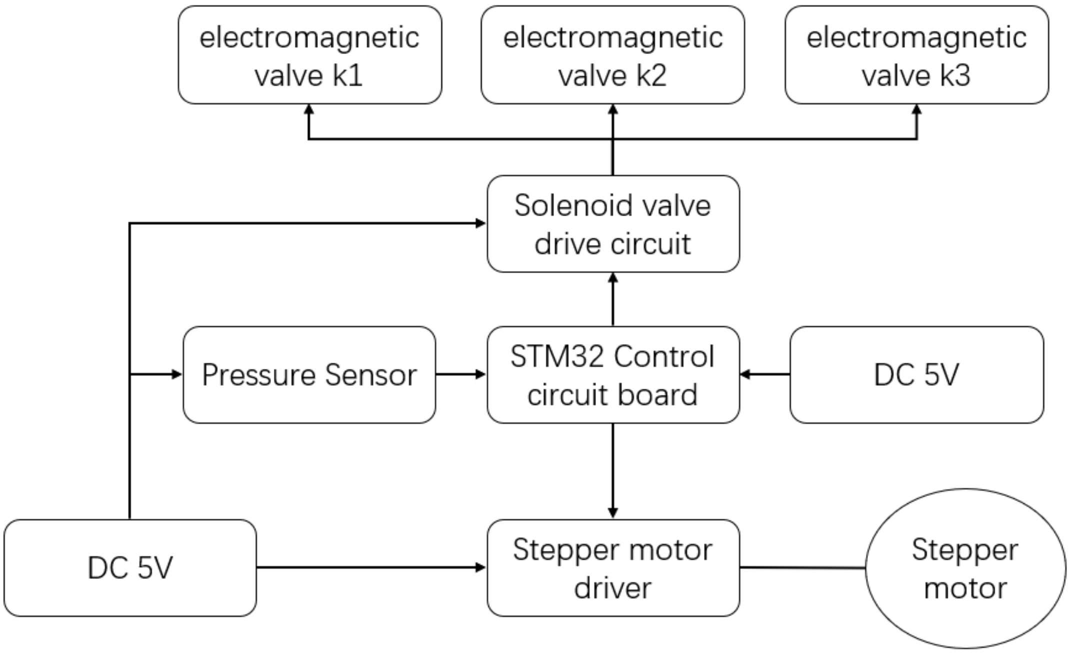

FIG. 2-9 Schematic diagram of control circuit

In order to drive and control the stepping motor, it is necessary to cooperate with the responding drive circuit or driver to drive. STM32 is configured as PWM output mode through internal timer resources, PWM signal through the driver to make the motor rotation.

2.3.5. Design of sampling head

The sampling head is the core design part of the sampling device for the high pressure and low temperature preparation kettle. Based on the design of each part of sampling head, the design of sampling head is finally completed through the overall assembly of each part model. The overall assembly drawing of the sampling head is shown in Figure 2-10. See Appendix 2 for the overall design of the sampling head.

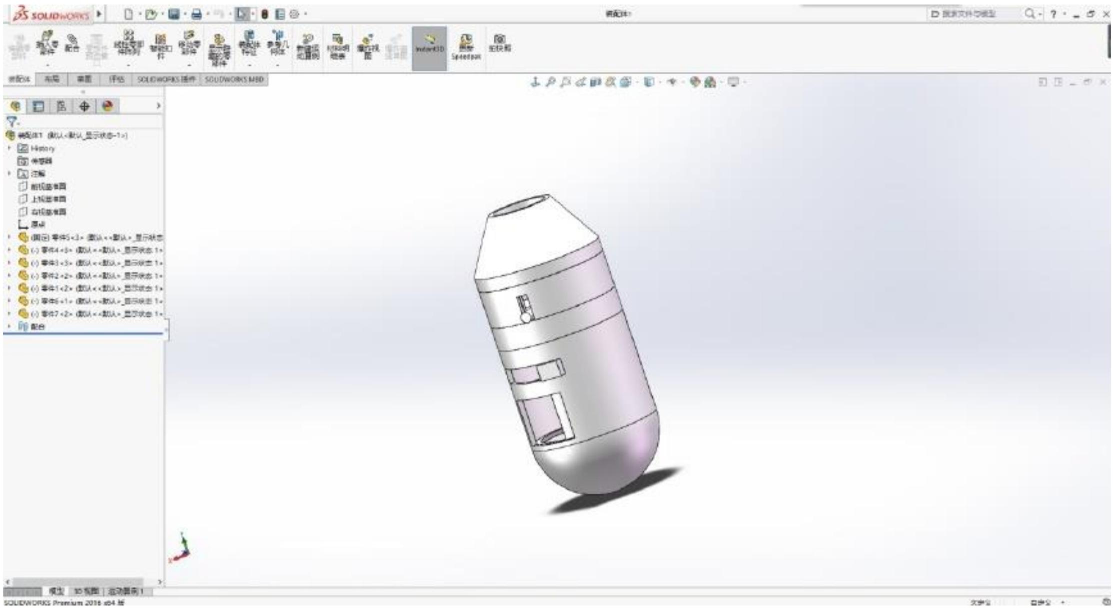

FIG. 2-10 Overall assembly drawing of sampling head

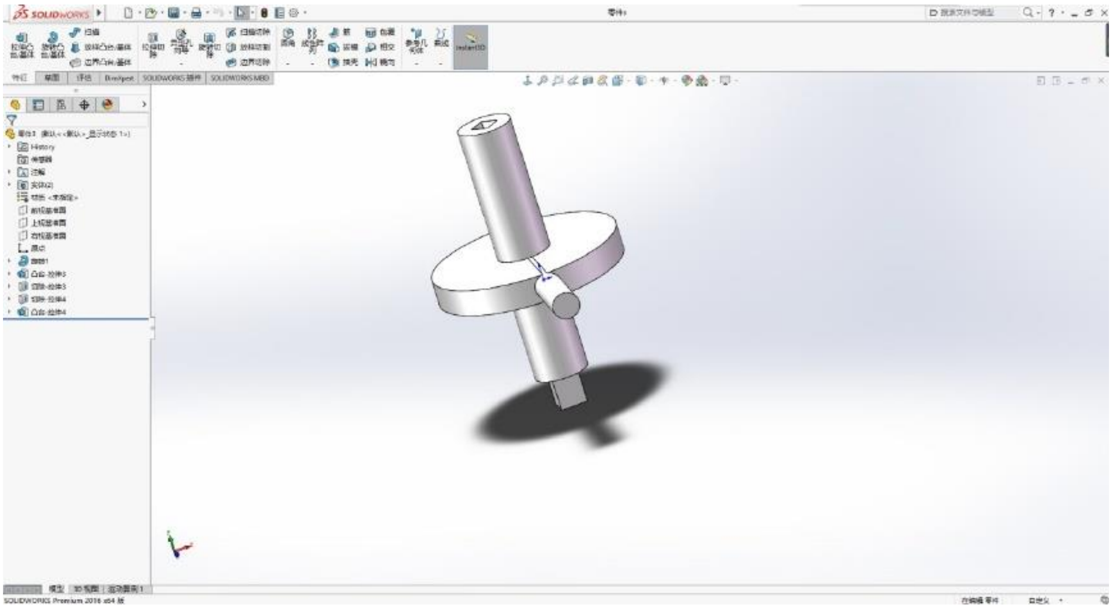

Figure 2-11 sample header clips

Sample header clips are shown in Figure 2-11. The sampling head clip is an important control part for the closure of the sampling head container. The upper part of the clip is directly connected with the flexible pipe layer flexible rope, and the lower part can jam the sampling head container door downward, so that the sampling head container is in an open state. The tester can directly move the middle protruding shaft to control its position in the sampling head. To start the sampling, push the clamp down so that the sampling head container door is in an open state.

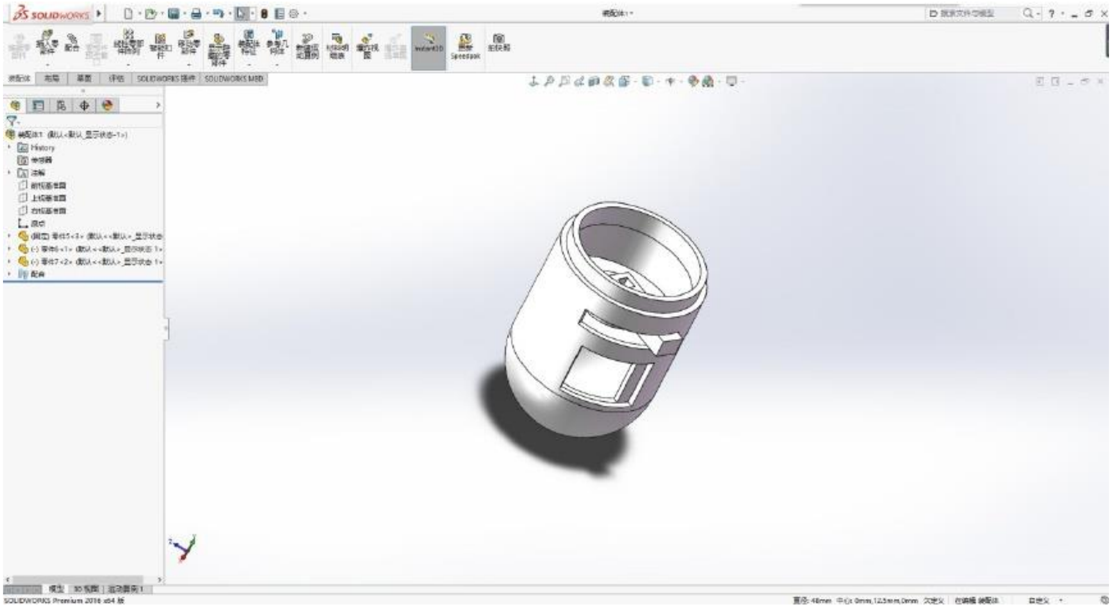

Figure 2-12 Sample head container assembly drawing

The assembly drawing of sampling head container is shown in Figure 2-12. The gas hydrates are hemispheric and cylindrical structures at the lowest end, and the containers can be opened or closed through a small door on the cylinder. It opens or closes by means of a torsion spring attached to the shaft of the door. When the door is in the open state, by pulling down the clamp, the torsion spring can be jammed to make the torsion spring under pressure Shrink to make the door open. When the clamp is pulled up, the torsion spring returns to its natural state to push the door to move and make the sampling head container close.

2.4. Studies pressure control system of pressure pipe

2.4.1. Research on pressure control system of pressure pipe

The main function of the pressure control system of the pressure pipe of the sampling device of the high-pressure and low-temperature preparation kettle is to precisely control the pressure inside the sampling pressure pipe. According to the design of the working mode of the controlled standby kettle, the control effect can be achieved by controlling the state of the intake valve K2 and exhaust valve K3 and by the feedback of the pressure sensor. FIG. 2-13 shows the block diagram of pressure control system of pressure pipe.

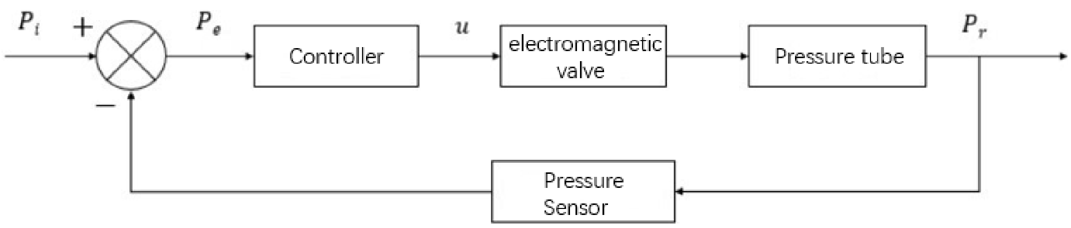

FIG. 2-13 Block diagram of pressure control system for pressure pipe

It mainly includes three processes of pressurization, pressure maintenance and pressure relief:

Pressurization process: when the pressure of the pressure pipe is lower than the pre-reached pressure, open the inlet valve K2 to inflate the pressure pipe and make the pressure inside the pressure pipe rise.

Pressure stabilization process: when the pressure inside the pressure tube reaches the preset pressure, stop the pressurization or pressure relief process. When the pressure has a relative change, change to pressurization or pressure relief process according to its change status.

Pressure relief process: When the pressure of the pressure pipe exceeds the preset pressure, open the exhaust valve K3 to exhaust the pressure pipe to reduce the pressure inside the pressure pipe.

In the sampling experiment, the pressure was controlled at 10MPa. Because the internal pressure is always in a state of change, in terms of the actual situation cannot reach a static equilibrium state, so we need to use a certain control method to reduce the fluctuation range of the low pressure, reduce overshoot, and can reach the dynamic equilibrium state as soon as possible. This chapter starts with the PID control commonly used in industry.

2.4.2. Pressure control simulation and analysis

Due to the high requirement of air pressure experiment on the experimental device, the rationality of controller design needs to be verified by simulation experiment in consideration of economic and safety factors. In this paper, MATLAB-Simulink simulation environment is used to simulate the controller performance, and compared with the conventional PID control and fuzzy PID control results.

According to the research and analysis on the air pressure control model of the closed system in literature, the actual air pressure control system is a time-varying and complex nonlinear control object, and its dynamic characteristics are shown in Equation (2-14).

$$G(s)=\frac{22.4}{22s+1}e^{-\tau s} \quad \text{Equation 2-14}$$

3. Summary

To achieve for Marine gas hydrates the diagenetic solid fluidization gas hydrate exploitation laboratory preparation of natural gas hydrate samples in a kettle sampling operation, this article through to the sampling processing of natural gas hydrate research both at home and abroad, in-depth analysis of the preparation conditions of gas hydrate and its preparation kettle structure, we design a suitable for the preparation of high-pressure low temperature state kettle sampling device. The device is a mechatronics system integrating mechanical design, sensor technology and control technology. Through the design of the hardware and software system of the device, the production and commissioning of the principal machine, the final experimental results basically meet the design requirements. The main work of this paper includes the following aspects:

(1) based on the research of diagenesis gas hydrate sampling device, on the basis of the analysis of natural gas hydrate formation conditions, on the basis of the concept of organic combination of mechanical and electrical apparatus, based on a magnetic coupling drive, electric drive dynamic integration of natural gas hydrate sampling device, and according to the Marine gas hydrates the diagenetic solid fluidization gas hydrate exploitation laboratory in the preparation of kettle structure analysis, determine the design of sampling device technical indicators, and completed the overall design of the plant.

(2) Based on the overall design scheme of the sampling device, the connection structure design of the sampling device and the sampling head structure design were completed, and the SolidWorks software was used to establish various part diagrams, and the assembly diagram of the device was finally completed. According to the functional characteristics required by the sampling device for the high-pressure and low-temperature preparation kettle, the selection of the controller, motor, magnetic material, sampling pressure tube wall material and pressure sensor of the sampling device was completed, and the design of the sampling head movement control circuit was completed.

(3) based on the sampling device of the hardware system design, completed the high low temperature preparation kettle sampling design of the pressure pipe gas pressure control algorithm, using the improved Smith forecast compensation fuzzy PID control algorithm to get the sample pressure tube to pressurize air pressure.

(4) Through the mechanical structure design drawing, the parts of the sampling device for the high-pressure and low-temperature preparation kettle were processed and assembled and adjusted to verify the rationality of the structural design. Through the laboratory simulation experiment of the principal machine of the sampling device, the results of this paper are verified to be correct in principle, reasonable in structure, innovative and practical, which provides technical support for the current and future practical non-diagenetic sampler for gas hydrate preparation.

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