Design and Experimental Study on Casing Pipe Continuous Flow Cryostat System

Sun Changli¹, Miao Dianyuan¹, Chu Dejun¹, Gao Junjie¹, Xu Hongbo²,*
1 China National Offshore Oil Corporation Energy Tech-Drilling & Production Co., Tianjin 300452, China
2 Technical Institute of Physics and Chemistry, CAS, Beijing 100190, China

Abstract
Casing pipe continuous flow cryostat system is the subsystems of liquid nitrogen freezing temporary plugging project. It is also an important supporting system which make the cooling uniform, safe and stable. The requirement analysis of cryogenic user have been carried out. The main technical specifications and requirements of the system has been defined. The process flow design and key components design have also been carried out. A verification experimental system has been built. The experimental results show that the design of continuous flow cryostat system is reasonable and the outlet temperature fluctuation is less than 0.3K, which can meet the design requirements.

Keywords: temporarily plugging, continuous flow cryostat system, well control technology

1. Introduction
Long distance pipelines have been used to transport crude oil since large quantities of oil were exploited. Pipes are usually buried underground and run all the year round. During oil transportation, the pipelines must be repaired, replaced, and process renovation etc[1]. While the traditional pipeline maintenance methods waste energy and pollute the environment. Pipe freezing, a process utilizing a refrigerant, particularly liquid nitrogen, to freeze liquid locally in a pipe to form a sealing plug [2]. Pipe freezing is an economically attractive technique employed in maintenance or repair [3]. The concern that the pipe will be altered by pipe freezing have been tested by metallurgical laboratories and major petroleum companies which, for various grades and sizes of pipe, report that the pipe properties are unchanged following controlled freezing techniques [4]. Temporarily plugging device based on the low temperature nitrogen gas cooling is a special equipment for maintenance and rescue of oil and gas well. When operating this device, high pressure will be applied to make the temporary plugging agent into each layer of the casing annulus and the inner side of oil and gas pipeline. After that, the low temperature nitrogen gas will be used to cool down the temporary plugging agent which has been moving in the casing annulus and oil and gas pipeline. The cooling power is gradually transferred from the outer tube to the inner. When the temporary plugging agent in the casing is cooled to a certain low temperature condition, the agent is tightly combined with the oil casing to form a bridge plug to make the annulus and oil and gas pipe sealed, so as to achieve isolation of the pressure in the well. Subsequently, it is safe to carry out the operation of replacing the oil and gas well-head or part of the gate valves above the freezing point [5].

Comparing to the traditional "drikold with methanol" cooling scheme, the above temporary plugging device has advantages like a short freezing time, no need to manually fill the refrigerant, controllable cooling target temperature, controllable cooling speed, and high adhesion strength of temporary plugging agent etc. While using low-temperature nitrogen gas as coolant is non-toxic, non-flammable, safe, and environmentally friendly. Therefore, the freezing temporary plugging technology based on low temperature nitrogen gas cooling is a preferred solution generally accepted in the industry, and the flow scheme is shown in figure 1. However, it is inevitable that the cooling casing should be equipped with a corresponding continuous flow cryostat system, as the uniform, safe, and steady cooling of casing deeply depend on the continuous flow cryostat system. The seal performance of the whole freezing temporary plugging device relies on whether the design of cryostat system is reasonable or not. The purpose of the study is to prove the feasibility of the cryostat system, and a verification test rig has also been described. Therefore, under the support of the
national key research and development plan names "public safety risk prevention and emergency technical equipment", CNOOC (China) Co. Ltd. carried out the research on liquid nitrogen freezing temporary plugging system, one of the most important technical breakthrough is the development of a casing pipe continuous flow cryostat system based on low temperature nitrogen gas cooling.

The International conference on Energy, Ecology and Environment (ICEEE) is created as words to describe a cross-discipline concerning shortage of energy resources, degradation of ecosystems and deterioration of environment. There have been changes in the course of history which has given specific emphases to the specific issues relevant for the respective period of these doctrines. However, the vision of sustainable development is often reflecting energy aspect and neglecting the ecological and environmental issues. No single discipline has the capacity to cope with these kinds of coupled complex issues. Growing interests have thus led us to integrate the main disciplines as our development strategy in order to adapt our future to the irreversible changes inherent in the human civilization. It has become evident that the complexity of such problems requires the need to enhance and deepening the understanding of the implications of different aspects of the development of the world. This international workshop aims to establish close links among these three fields, set up systems science based on knowledge from other sciences and promote multidisciplinary solutions to settle the complex social-economic and environmental problems.

2. Process design of the system

2.1 Cooling requirements of users

The main goal of this cryostat system is to use cold nitrogen gas to cool down the oil and gas well casing by the method of jacketed cooling. As the casing is mainly consisting of low-carbon steel and low-alloy steel, so the casing’s freezing property and safety are decided by the casing steel mechanical behavior at low temperature which is considered when designing the system.

In general, when steel is immersed from a room temperature into a lower temperature environment, the carbide in the steel turns more refined and evenly distributed, and the yield strength, tensile strength of the steel are also increased [6]. Therefore, after the oil and gas casing is cooled down, its strength and pressure bearing capacity are improved to meet safety requirements.

![Figure 1](image1.png)

**Figure 1** The flow scheme of temporarily plugging device

![Figure 2](image2.png)

**Figure 2** Results of low temperature impact experiment

At the same time, it cannot be ignored that these casing materials are generally body-centered cubic lattice steels, which are prone to cold crisp [7]. So as to avoid the brittleness failure of casing during freezing, the experimental research must be carried out on the cold crisp of casing materials which will provide reference for process design and corresponding control strategies for cryogenic systems. In this paper, common steels for oil and gas casing have been made statistics, some representative steels like H40, N80-Q, Q125, L80-1 were selected for brittle impact test at different temperatures -196°C, -110°C, -78°C, -50°C, 25°C. The experiment was based on the Chinese national standard GB/T229-1994, and the JBS-300B digital impact tester was used. The pendulum energy is 150 J, The empty pendulum energy is 0.15 J. The sample at 25 °C was first immersed in liquid nitrogen and then completely re-warmed before the experiment, the specific experimental results are shown in figure 2. It can be seen from the comparison results that the sample which was first immersed in liquid nitrogen and then completely re-war-med showed good impact resistance performance at room temperature, better than the requirements of relevant standards (such as: GB150.2-2010). The impact resistance performance of all materials decreases with decreasing temperature. Therefore, in order to avoid the safety hazard caused by low temperature and cold crisp, it is necessary to use a thermostat to wrap the frozen target during freezing, to perform necessary protection on the frozen part, to control the target temperature during cooling, to maintain a certain temperature margin, to ensure that target has a certain residual toughness and can withstand a common impact to some extent.
And another problem that cannot be ignored is the thermal stress of the casing and other cooling parts when they were cooling down, because of the temperature gradient causing by the too fast cooling rate. So, the cooling rate of the frozen target needs to be strictly controlled by the cryogenic system according to the actual situation of the freezing.

In summary, continuous flow cryostat system must have the following characteristics. 1) It can deliver a certain flow rate and a certain temperature of cold nitrogen gas to the frozen target, 2) The temperature and flow rate of the supplied cold nitrogen gas can be adjusted within a certain range, 3) The frozen casing requires a fully wrapped thermostat, 4) The freezing state of the frozen target must be monitored in real time, and the control system can adjust the cooling strategy according to the actual situation.

2.2 Organizational structure of system processes

According to the above analysis and the technical requirements of the supporting equipment, the process design of the cryostat system was carried out. This system mainly includes liquid nitrogen storage tank (pressurizable), air temperature heat exchanger, set of valve blocks, nitrogen mixer, adiabatic low temperature transmission line and user side thermostat, and the specific scheme is shown in figure 3. When the wellhead needs to supply liquid nitrogen, closing valves V1, V21 and V3, opening valve V22, the flow rate of liquid nitrogen from the liquid nitrogen storage tank is controlled by controlling the opening of V2. When the wellhead needs to supply cold nitrogen gas, closing valve V22, opening valves V3 and V21, the control strategy set by the measurement and control system automatically controls the opening of V1 and V2 to obtain the required cold nitrogen flow rate and suitable temperature. Among them, the liquid nitrogen in the V1 road is vaporized by the air-temperature heat exchanger to become normal temperature nitrogen gas, and mixed with the liquid nitrogen in the V2 road at the nitrogen mixer, a suitable ratio of V1 and V2 opening will allow the nitrogen gas to form an appropriate temperature cold nitrogen gas after leaving the nitrogen mixer to cool down the head of the well. Both liquid nitrogen and cold nitrogen gas will be delivered to the cryogenic thermostat on the user side through an adiabatic cryogenic transfer line.

When the system needs to be purged or re-warmed, the controlling system will close valves V2, V21 and V22, open the valve V3, and control the opening of V1 to obtain a certain flow rate of dry nitrogen gas at room temperature. If it is necessary to obtain dry nitrogen gas above normal temperature, the electric heating device in the nitrogen mixer can be turned on, and the required nitrogen gas temperature is set by the measurement and control system, the power of the heating device is automatically controlled by the system.

![Figure 3 Flow diagram of cryogenic system](image)

3. Structural Design of key components

As mentioned in the process design part, there are two key components in the system: nitrogen mixer and casing pipe continuous flow cryostat on the user side. The function of the nitrogen mixer is to thoroughly mix a certain flow of normal temperature nitrogen gas and liquid nitrogen, and provide cold nitrogen gas with stable temperature and small fluctuation to the flow downstream. The function of the casing continuous flow cryostat is to provide a relatively uniform cooling annulus for the casing to be cooled, to improve the efficiency of the utilization of cold nitrogen gas, and to ensure a smooth cooling of the casing. The design details of these two non-standard key components will be shown as followed.

3.1 Nitrogen mixer

The structure of the nitrogen mixer is shown in figure 4, it includes liquid nitrogen inlet, normal temperature nitrogen gas(\(\text{NN}_2\)) inlet, cold nitrogen gas(\(\text{CN}_2\)) outlet, stainless steel temperature-mixing kettle, liquid nitrogen spray atomizer, lateral adiabatic support, stainless steel wire mesh, insulation packing, bottom support and thermometers, etc[8]. When the mixer is working, liquid nitrogen enters the kettle from the top inlet, and is dispersed into small particles of atomized in the spray atomizer, and is fully mixed with the normal temperature nitrogen gas from the bottom of the kettle, a small amount of relatively large droplets are intercepted by a multi-layer stainless steel wire mesh, which will further enhance the heat exchange between the high and low temperature fluids, then the mixed cold nitrogen gas is discharged from the nitrogen gas outlet. The whole stainless steel kettle is fixed in the mixer casing by a plurality of lateral supports and a bottom support, and the interlayer between the kettle and the mixer casing is filled with a heat insulating materials, wherein the bottom of the kettle is at a normal temperature, so the bottom support is a fixed support of the ordinary structure,
while the lateral support is located in the middle of the kettle, the temperature thereof is low, so the lateral support uses an adiabatic support with a lower thermal conductivity. In order to further evaluate the warming effect of the mixer, a plurality of thermometers are also arranged in the upper, middle and bottom portions of the temperature-mixing kettle.

![Figure 4 Structure of nitrogen mixer](image)

### 3.2 Casing pipe continuous flow cryostat

The structure of the casing pipe continuous flow cryostat is shown in figure 5, it includes a pair of semi-circular jackets (with jacket butt extension), jacket inner insulation, cold air deflector, cold nitrogen inlet and outlet, and several thermometers arranged along the axial direction. Before operating the cryostat, an appropriate jacket thermostat should be chosen according to the size of the casing, and complete the combination of a pair of semi-circular jackets, if necessary, add a sealing strip at the joint to ensure that the whole device has a certain air-tightness. Cold nitrogen gas is introduced from the nitrogen inlet at the bottom of the cryostat, and then through the deflector, the cold nitrogen gas will be rectificated to enhance the effect of the cooling-convection of the gas, and the cooled cold nitrogen gas is finally merged to discharge from the nitrogen outlet of the cryostat.

![Figure 5 Structure of casing pipe continuous flow cryostat](image)

Several thermometers are placed on the cryostat and casing to detect the entire cooling process. A plurality of thermometers are evenly arranged axially on the outer wall surface of the casing for detecting the wall temperature of the casing, ensuring the casing cooling process at a safe temperature. The system will also record historical data of these temperatures to ensure that the cooling rate is not too fast. By comparing the temperature difference between these thermometers, the temperature gradient of the outer wall of the casing can be further investigated to ensure cooling down casing uniformly, so as not to be damaged by thermal stress.

At the same time, thermometers are arranged at the inlet and outlet of the device for monitoring the temperature of the cryostat. The main logic of the control is that controlling the cooling temperature of the casing through the inlet temperature of the cryostat and controlling the flow rate of cold nitrogen gas through the temperature difference between the inlet and outlet of the cryostat. Excessive temperature difference between the inlet and outlet indicates that the flow rate of cold nitrogen gas is not enough, which may cause uneven temperature reduction. While the temperature difference between the inlet and outlet is too small means that the flow rate of cold nitrogen gas is too large, and the cooling capacity is not completely utilized, which affects the economics of the system.

### 4. Experimental study on performance of cryostat system

In order to further develop the experimental research on the performance of the cryostat system, a test verification device is built according to the flow diagram in figure 6 the specific experimental verification device is shown in figure 7. The liquid nitrogen source is a 200 L self-pressurized liquid nitrogen tank, an air-bath type vaporizer with a gasification amount of not less than 180 Nm³/h and a self-developed nitrogen mixer were used.

![Figure 6 Flow diagram of verification cryogenic system](image)

Firstly, the liquid nitrogen tank should be pressurized, then open the valve V2 so as to sent the pressurizing liquid nitrogen out through the air bath to become normal temperature nitrogen gas. The whole system is purged with normal temperature and dry nitrogen gas. In particular, it is necessary to remove moisture from the system to avoid ice blockage at low
temperatures. Adjusting the valve V1 to send a part of the liquid nitrogen to the mixer and mixing with the normal temperature nitrogen gas. The mixed cold nitrogen gas is sent to the downstream through the low temperature transmission line. In the experimental device, a thermometer is set at the cold nitrogen gas exhaust port of the mixer to monitor the temperature situation.

![Image of verification cryogenic system](image)

**Figure 7** The photo of verification cryogenic system

In order to test the performance of the mixer, the opening of V2 was maintained after purging the system, and the valve V1 was opened at a certain opening and kept it until the end of the experiment. During the test, the other valves did not move, the supply pressure of the liquid nitrogen cold source did not change significantly, the system air supply was kept at about 10 g / s, and the temperature of the outlet of the mixer was collected and recorded every 5 seconds. The specific recorded data is shown in figure 8. Through the experiments, it can be found that the system takes about 15 minutes to cool down from normal temperature to about 180 K and becomes constant. By analyzing the temperature measurement data for the last 120 s, the average temperature at the end of the equilibrium was 182.87 K, and the temperature fluctuation was ±0.27 K, having been met the design requirements.

![Image of outlet temperature trend](image)

**Figure 8** Outlet temperature trend of mixer during cool-down

### 5. Conclusion and prospect

A casing pipe continuous flow cryostat system based on low temperature nitrogen gas cooling is designed to realize controlled cooling of the casing by conveying a controlled flow rate and controlled temperature of cold nitrogen gas to the special cryostat for the casing. The original freezing device has a long cooling time, uncontrollable cooling target temperature, uncontrollable cooling speed, etc. which has been replaced to reduce the working intensity of the artificial site, save the labor costs, improve the safety of the freezing process and the strength of freezing, and the exhaust gas generated by the equipment is non-toxic, harmless, non-flammable, safe and environmentally friendly. In order to prove the feasibility of the design, this paper also describes a verification test rig, it has been proved that the system design is reasonable. In the vicinity of the operating condition, the outlet temperature of the mixer fluctuates within 0.3 K, meeting the design requirements.

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### Reference


