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Design and Experimental Study of an Improved Pressure Core Sampler for Marine Gas Hydrates

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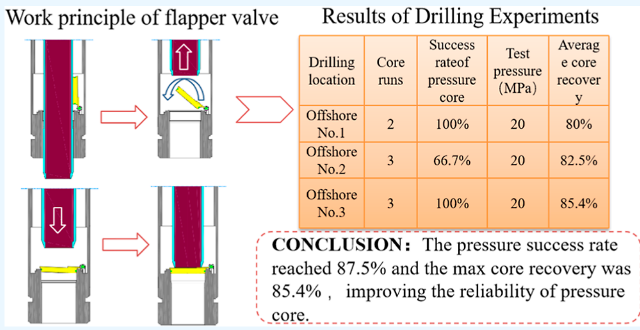
ABSTRACT: A pressure core sampler (PCS) is considered an effective tool to retrieve marine gas hydrate cores from hydrate-bearing sediments. However, according to the sampling application statistics, the success rate of pressure coring changed from 30% to 85% in different drilling wells. Such severe fluctuation will cause huge uncertainty in the practical application of technology and economic benefits. Herein, we present a new PCS designed to improve pressure-retaining reliability. The work principle, design and calculations, and structure composition were described. Through the laboratory tests and drilling experiments, the maximum holding pressure in the pressure chamber was 32.1 MPa, and the pressure loss rates of holding pressure after 2 h changed from 1.96% to 2.46%. The maximum temperature-rising value in the pressure chamber was 0.96 °C under a temperature of 23.5 °C in 2 h. Furthermore, the success rate of the pressure core reached 87.5% and the core recovery was not less than 80%, which were verified by 8 pressure core runs in three different offshore wells. Therefore, we conclude that this new and improved PCS has great application value in gas hydrate exploration that seeks to recover more accurate cores in situ, especially in the silt and sand layers.



1. INTRODUCTION

Natural gas hydrates are widely distributed in permafrost regions and beneath the seafloor sediments on continental slopes at low-temperature and high-pressure conditions.[1,2] An estimated 3×10^{14} m^3 of gas hydrates is considered as one of the most promising clean energy resources in the future due to its advantages of low pollution, high energy density, and shallow buried depth.[3,4] To better understand the formation and migration of gas hydrate, as well as the role of natural gas in the global carbon cycle, high-quality core samples of hydrate-bearing sediments are indispensable.[5−7] As we all know, conventional coring tools are often recovered with highly disturbed samples due to the dissociation of gas hydrate, exsolution, and degassing during core sampling.[8,9] Thus, pressure coring technology has been developed which allows scientists to recover hydrate-bearing cores with high pressure (>200 bar) and low temperature(<10 °C) during the sampling, transportation, and storage.[10−12] Moreover, this technology eliminates or at least alleviates the influence of gas hydrate decomposition to disturb the cores.[13,14] Once the pressurized cores are successfully recovered, scientists can conduct geological, geotechnical, geochemical, and microbiological tests for assessing the nature, distribution, and concentration of gas hydrates under the in situ condition.[15,16] Furthermore, they also provide ground-truth data for marine hydrate exploration and trial production.

In general, pressure coring tools have been deployed successfully over the past few decades. So far, the pressure samplers with good performance in application include pressure core barrels (PCBs) in the Deep Sea Drilling Project (DSDP),[17] the pressure core sampler (PCS) in the Ocean Drilling Project (ODP), the Fugro pressure corer (FPC)/HYACE rotary pressure corer (HRC) developed by EU-funded HYACE/HYACINTH programs,[18,19] and the pressure−temperature core sampler (PTCS) and hybrid PCS developed by Japan.[20] The parameters and using records of different pressure corers are shown in Table 1. All of these pressure corers are furnished with a ball valve or flapper valve to seal the cores into the core barrel, which is considered as the pressure chamber. However, according to the pressure coring statistics, more than 30 percent of pressure cores obtained from hydrate-bearing sediments recovered by current pressure corers hold no pressures or much less than the in situ pressures. In numerous reasons for the failure of the pressure

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Table 1. Technical Parameters and Sampling Records of Different PCSs[a]

PCSs	coring method	core diameter (mm)	max core length (m)	working pressure (MPa)	sampling records
PCB	wire line	58	5.8	34.4	ODP Leg19/42B/44, blake outer ridge
PCS	wire line	43.2	1	69	ODP Leg164/201/204,[28] IODP expedition 311, NGHP 01 of India[29]
FPC/HRC	wire line	53.97	1	25	ODP Leg201/204, IODP expedition 311, Gulf of Mexico JIP Leg 01,[30] NGHP expedition 01 of India, GMGS expedition 01 and 02 of China,[31] UBGH Expedition 01 and 02 of Korea
PTCS	wire line	66.7	3	24	Nankai Trough Project of Japan in 1999 and 2000, Nankai Trough Project of Japan in 2004[13]
hybrid PCS	wire line	51	3.5	35	Nankai Trough Project of Japan in 2012, Expedition 802 of Nankai Trough Project[13]

[a]Abbreviations: PCB = pressure core barrel; PCS = pressure core sampler; FPC = Fugro pressure corer; HRC = hydrate autoclave coring equipment rotary corer; PTCS = pressure temperature core sampler; Hybrid PCS = Hybrid pressure core sampler; ODP = Ocean Drilling Program; IODP = International Ocean Drilling Program; NGHP = National Gas Hydrate Project; JIP = US Joint Industry Project; GMGS = China Geological Survey Guangzhou Marine Geological Survey; UBGH = Korea Korean National Gas Hydrate Program Ulleung Basin Gas Hydrate Drilling Expedition; Nankai Trough = Japanese Methane Hydrate Research and Development Program.

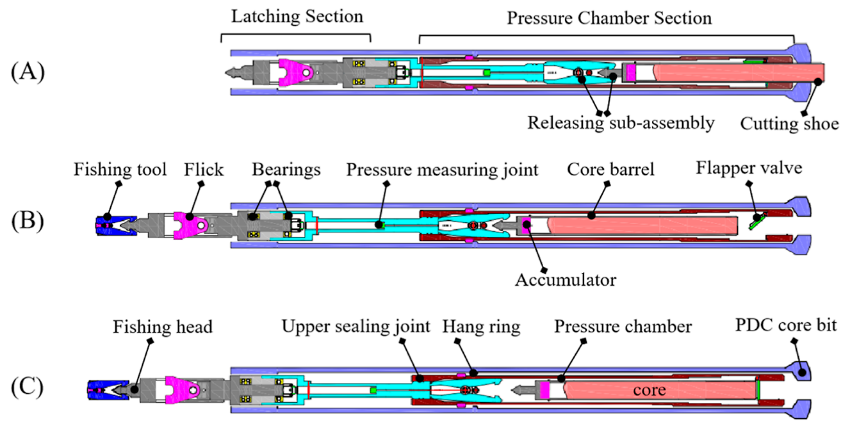

Figure 1. IPCS with flapper valve configurations. (A) During the drilling process, the BHA drills into the formation with rotation. Meanwhile, the core enters into the core barrel, and the flapper valve is open; (B) During the recovery process of the CBA, the fishing head is pulled upward by the fishing tool to recover the core barrel into the pressure chamber, and the plate valve turns over under gravity; (C) During the reliable closing stage of- flapper valve, the CBA continues to pull upward. After the flapper valve is closed but not well, the core barrel with cores will fall off from the CBA under the action of the travel control switch and press on the flapper valve to ensure it is closing tightly.

Table 2. Technical Parameters of the IPCS

type	sampling method	core diameter	max core length per run	pressure capacity	core bit OD	the whole length of the CBA
HYB-1	wire-line method	50 mm	2.5 m	the maximum pressure capacity is more than 30 MPa, and the pressure loss rate within 2 h of pressure holding is not more than 10%	215.9 mm	5.3 m

core, the success rate of pressure coring changed dramatically from 30% to 85%.[21−23] The most frequent occurrence was ball valve or flapper valve seal damage because of the silt and sand adhering to the seal surface.[24,25] Such a high-precision valve works in the fluids filling with abundant small solid particles produced by borehole drilling.[26,27] As a result, the sealing performance can be easily deteriorated. Although significant scientific achievements have been obtained by using the pressure corers mentioned above, it is still a huge challenge to improve the success rate of the pressure core and decrease the cost of deployment.

In view of these problems relevant to the pressure corers, this paper comes up with an improved PCS (IPCS) to overcome the sealing failure on the flapper valve. The working principle, design, and calculation processes and structure composition of the IPCS were described. Through laboratory tests and field experiments, the pressure loss rate and temperature-rising value of the IPCS were kept in an allowable range for 2 h. Most importantly, the success rate of the pressure core and core recovery were verified by 8 core runs. Based on the above research results, the IPCS provides a promising solution to develop new pressure corers with good performance for marine gas hydrates' exploration.

2. DESIGN METHOD FOR THE IPCS

According to the characteristics of marine hydrate sediments and referring to pressure core requirements, this study aims to improve the pressure core success rate and core recovery.

2.1. Working Principle of the IPCS. The PCS was used in 1984 for the DSDP. After that, the pressure core was continuously optimized, and the performance of the pressure core became better and better. On the basis of previous research on the PCS, this paper presents an IPCS (Figure 1) to enhance the success of flapper valve sealing. The technical parameters of the IPCS are shown in Table 2.

The IPCS in Figure 1 is made up of a core barrel assembly (CBA) and a borehole assembly (BHA) (the light-blue section in Figure 1). The CBA is in the BHA, which is composed of a latching section and a pressure chamber section. The BHA is

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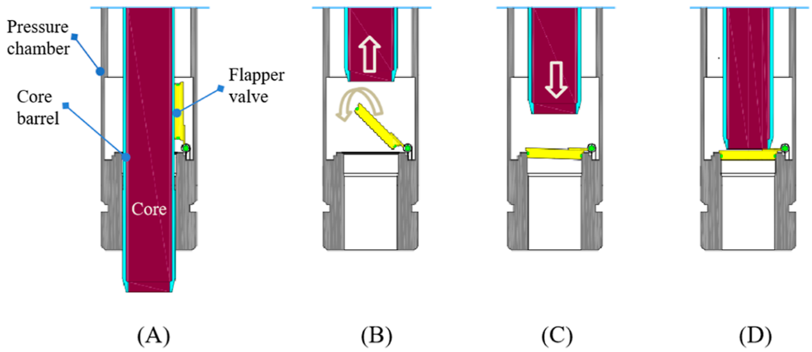

Figure 2. Flapper valve reliable closing diagram. (A) When drilling, the flapper valve is open and the core enters the core barrel. (B) After completion of drilling, the core barrel is returned to the pressure chamber, and the flapper valve turns over under gravity. (C) The flapper valve has been closed, but maybe it is not closed well. Then the core barrel begins to fall with the travel control switch. (D) The core barrel falls onto the flapper valve and presses the flapper valve to achieve reliable sealing.

connected to the bottom of the drill strings and is used to deploy the CBA. Once samples begin to be taken up, the CBA is delivered by a wire-line tool and locked into the BHA (Figure 1A), and then the BHA is rotated and drilled. When the drilling footage reaches the length of the core run, the CBA is lifted upwardly, the flapper valve is closed, and the pressure chamber is sealed, and finally, the CBA is retrieved (Figure 1B,C).

The BHA mainly includes a connection pipe, hanging ring, and PDC core bit. The top of the BHA is connected to Φ127 mm drill pipes, of which the inner diameter is 105 mm for wire-line sampling operations. The hanging ring is used to position the CBA. Considering that the hydrate reservoir is unconsolidated and prone to erosion by drilling fluid, the water holes of the PDC core bit are designed to be bottom jet for reducing core erosion. The front end of the core barrel advances the PDC core bit 80−100 mm to improve the core recovery.

As one of the most important parts, the latching section of the CBA consists of a fishing head, flick, and bearings. Its main function is to keep suitable locking/unlocking and retrieving of the CBA into or from the BHA. The pressure chamber section contains a pressure measuring joint, upper sealing joint, releasing subassembly, pressure chamber, accumulator, core barrel, and flapper valve (in Figure 1B,C). This section is the key component to maintain the sealing of the pressure core. As we all know, there are a large number of solid particles suspended in the drilling fluid at the bottom of the well. This work condition makes it very easy for solid particles' accumulation to occur near the sealing surface, causing sealing failure of the flapper valve. Thus, an innovative technical method is adopted to improve the reliability of flapper valve sealing in vertical wells (Figure 2). This method can be divided into three steps: (1) during drilling, the flapper valve is opened and the core enters into the core barrel (Figure 2A). To improve core recovery, small pump displacement, slow rotation, and low weight on bit are used. (2) After reaching the maximum coring length, the fishing tool should be first used to catch the fishing head of the CBA and then pulled upward for 0.5 m. At the same time, the core barrel is lifted into the pressure chamber. When the core barrel passes upward over the flapper valve, the flapper valve will turn over under self-weight (Figure 2B). (3) When the core barrel continues to be lifted up, the pressure measuring joint enters the upper sealing joint to seal the top of the pressure chamber (in Figure 1B). At this time, the releasing subassembly is triggered and the coring barrel with the core is released downward, impacting the flapper valve for good closing and reliable sealing (in Figure 2C,D).

2.2. Design Calculations of Key Parameters. *2.2.1. Deformation Calculation of the Pressure Barrel.* When the IPCS takes samples at the bottom of the sea, the inside of the pressure barrel is connected with the external seawater, and the internal and external pressure is balanced, so the pressure barrel itself does not produce elastic deformation. Then the core barrel is lifted into the pressure barrel to complete sampling, and the upper and lower part of the pressure barrel is sealed. After the IPCS is raised to sea level, the in situ pressure of the sampling point is still maintained in the pressure barrel, while the pressure outside the pressure barrel drops to normal atmospheric pressure, which produces a large pressure difference between the internal and external pressure. Under differential pressure, the pressure barrel will generate some elastic volume expansion. According to the radial and axial changes of the pressure vessel under the action of pressure difference, the theoretical volume variation of the pressure barrel can be calculated.

Based on the elastic theory, the formula of radial and axial deformation of a pressure barrel subjected to internal and external pressure differences can be derived.

$$u = \frac{D_i^2 P_i}{rE(D_o^2 - D_i^2)}[r^2(1 - 2\mu) + D_o^2(1 + \mu)] \quad (1)$$

$$\Delta L = \frac{D_i^2 P_i L}{E(D_o^2 - D_i^2)}(1 - 2\mu) \quad (2)$$

Thus, the volume change of the pressure barrel is

$$\Delta V = V_2 - V_1 = \frac{\pi}{4}(D_o + u\Delta^2(L + \Delta L) - \frac{\pi}{4}D_o^2 L \quad (3)$$

In eqs 1−3, μ is the radial deformation, ΔL is the axial deformation, L is the length of the pressure barrel, ΔV is the volume change, P_i is the internal pressure, E is the elasticity modulus of the pressure barrel, μ is Poisson's ratio, D_i is the inner diameter of the pressure barrel, D_o is the outer diameter of the pressure barrel, and r is the radius of the calculation position.

2.2.2. Thickness Calculation of the Flapper Valve. The flapper valve is the key component to seal the bottom of the pressure barrel. According to the formula calculation of the pressure vessel, we can find out how to ensure that the flapper

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valve has enough thickness with permission for deformation under the internal pressure. Through the seal ring installed on the flapper valve, the mechanical face seal makes the bottom of the pressure barrel seal well.

$$t = D_i\sqrt{\frac{0.31P_i}{[\sigma]}} + C \tag{4}$$

In eq 4, t is the thickness of the flapper valve, $[\sigma]$ is the allowable stress of the material, and C is the additional wall thickness.

2.2.3. Accumulator Volume Calculation. Using an accumulator is one of the effective ways to avoid pressure reduction due to deformation of the pressure chamber for the PCS. The accumulator should be filled with high-purity nitrogen before running in the well. The prefilling pressure is generally 80−90% of the working pressure at the sampling position. In order to keep enough pressure in the pressure chamber, the accumulator volume should be calculated.

$$V_0 = \frac{\Delta V}{P_0^{1/n}\left[\left(\frac{1}{P_1}\right)^{1/n} - \left(\frac{1}{P_2}\right)^{1/n}\right]} \tag{5}$$

In eq 5, V_0 is the volume of the accumulator, P_0 is the prefilling pressure of the accumulator, P_1 represents the pressure in the accumulator when the IPCS is lifted to the drilling ship, P_2 represents the pressure in the accumulator when the IPCS is at the sampling location, and n is the adiabatic index. In general, the adiabatic index of nitrogen is 1.4.

According to the pressure requirement of at most 30 MPa and the limitation of the drill tool size, the calculation results of key parameters are shown in Table 3. The materials of the drilling tool are 42CrMo and stainless steel 316L.

Table 3. Calculation Results of Key Parameters

parameter	valve	parameter	valve
the outer diameter of the pressure barrel	90 mm	the inner diameter of the pressure barrel	75 mm
the length of the pressure barrel	3.5 m	the thickness of the flapper valve	8.5mm
the diameter of the flapper valve	62 mm	the volume of the accumulator	350 cm^3
the max prefilling pressure of the accumulator	24−27 MPa	the inner diameter of the drill pipe	105 mm

3. EXPERIMENTS ON THE IPCS

3.1. Pressure and Temperature Tests. In order to test the pressure holding performance of the IPCS, pressure and temperature tests were carried out. As shown in Figure 3, the test system mainly included injecting lines, a pressure sensor, a data recorder, fixed trestles, a crane, a pressure chamber, and a temperature and pressure collector (in Figure 4) which was installed into the pressure chamber. The experiment medium was clean water, and the ambient temperature was 23.5 °C. Moreover, the pressure holding time was set to 2 h, which was determined based on the processes of retrieving the IPCS from the well bottom, checking drilling tool integrity, testing the pressure, and transferring the pressure chamber to the lab.

Before the test, the clean water was cooled to 3.90 °C to simulate the seabed temperature, and then the water was injected into the pressure chamber through injecting lines. During this process, the pressure sensor was used to monitor the pressure of the test system. According to the marine hydrate sampling requirements, the maximum pressure holding capacity of the IPCS should not be less than 30 MPa. In the pressurization process, the method of stage pressurization was used. It was stopped for 3−5 min every time the pressure rose by 5 MPa and checked to see whether the thread connections between the pressure chamber and flapper valve leaked. After the pressure in the pressure chamber reached 30 MPa, the injecting lines were closed. Then the pressure holding stage lasted for 2 h. The temperature and pressure collector installed in the pressure chamber was used to acquire temperature and pressure data (in Table 4).

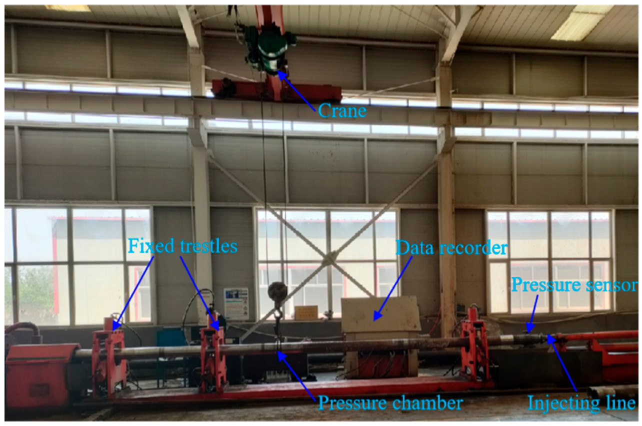

Figure 3. Pressure and temperature tests of the IPCS.

3.2. Results and Discussion of Pressure and Temperature Tests. As can be seen from Table 4, three tests were conducted. The maximum pressure in the pressure chamber was 32.1 MPa, and there was no leakage and component failure. It was proved that the IPCS could have a certain pressure overload. In these three tests, the pressure loss rates changed from 1.96% to 2.46%, which was far less than the design requirement of 10%. This may be related to the residual air in the pressure chamber when the cooled water was injected. In addition, the temperature-rising values were 0.93−0.96 °C, and the maximum temperature after 2 h was 4.86 °C.

On the basis of the marine hydrate phase equilibrium curve, with the pressure of 30 MPa, the gas hydrate would not be decomposed below 12.5 °C.[32,33] Thus, in this environmental condition of test results, the hydrate core in the pressure chamber could be kept in a stable state. Through the pressure and temperature tests, the key calculation parameters of the IPCS were verified to be effective, and the pressure chamber could also maintain the pressure and temperature in an acceptable range.

3.3. Drilling Experiments. After the pressure and temperature tests of the IPCS, the experiments of sampling tests were conducted a total of 8 times by using Marine no.10 and Binhai no.66 drilling vessels, which were equipped with a DP-2 dynamic positioning system and mooring positioning system. The experimental water depth was 39.8−60 m, and the layer less than 60 m of the seabed was silty clay and sandy clay. This kind of formation was very similar to that of hydrate strata in the deep sea. The drilling tool assembly used in experiments mainly included IPCS (core bit OD 215.9 mm) + drill collar (OD 190 mm, ID 105 mm) + drill pipe (OD 127 mm, ID 105 mm). The core was obtained by the wire-line method.

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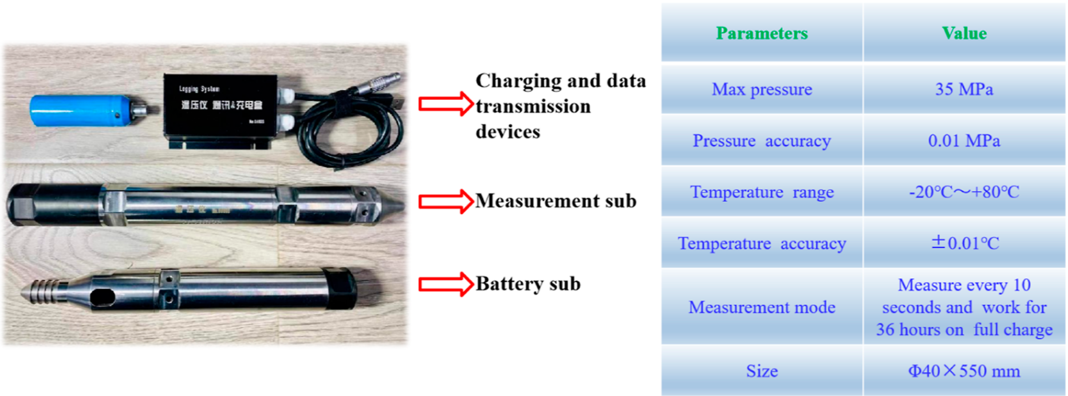

Figure 4. Parameters of the temperature and pressure collector.

Table 4. Pressure and Temperature Changes in the Tests

number of tests	initial pressure (MPa)	pressure after 2 h (MPa)	pressure loss rate (%)	initial temperature (°C)	temperature after 2 h (°C)	temperature-rising value (°C)
no. 1	32.10	31.47	1.96	3.90	4.86	0.96
no. 2	30.50	29.75	2.46	3.92	4.85	0.93
no. 3	29.50	28.84	2.24	3.90	4.85	0.95

Before drilling, the BHA, drill collar, and drill pipe were connected successively and lowered into the well bottom. Then the accumulator was inflated with nitrogen, whose pressure is 85% of the water depth in the well. Next, the CBA was placed into the BHA by means of wire-line tools. During the core drilling processes, the drilling parameters were adjusted according to formation conditions. The primary objective was to improve core recovery in the unconsolidated stratum. Due to the shallow water depth of drilling tests, the pressure in the IPCS retrieved by the wire line was relatively small, most of which was lower than 1 MPa, so it was difficult to judge the pressure-preserving effect. To solve this problem, an electric pressure pump was applied to increase the pressure of the IPCS, and the maximum pressure was set to 20 MPa. After completion of pressurization, the pressure was kept constant for 15 min. If there was no leakage in the IPCS, it was proved that the pressure sampling was successful. Then the core was taken out from the core barrel, and the core recovery was calculated. The experimental processes are shown in Figure 5 and the drilling parameters and results of experiments are presented in Table 5.

3.4. Results and Discussion of the Drilling Experiments. As can be seen from Table 5, the flapper valve was closed 7 times in 8 coring tests (in Figure 6), and the pressure-preserving effect could be proved through the pressure tests. The success rate of pressure preservation was 87.5%, and the maximum core recovery was 85.4%. Even if the minimum core recovery was 80%, it would have still met the requirement for hydrate sampling. It was notable that one-time pressure failures happened mainly because the flapper valve was not closed well. The reason was that the strata changed from silty clay to sandy clay, and more sand particles suspended in the drilling fluid gathered around the flapper valve, which eventually led to sealing failure. Through the drilling tests on the offshore, the results show that the IPCS could effectively improve the success rate of pressure sampling and also have enough core recovery.

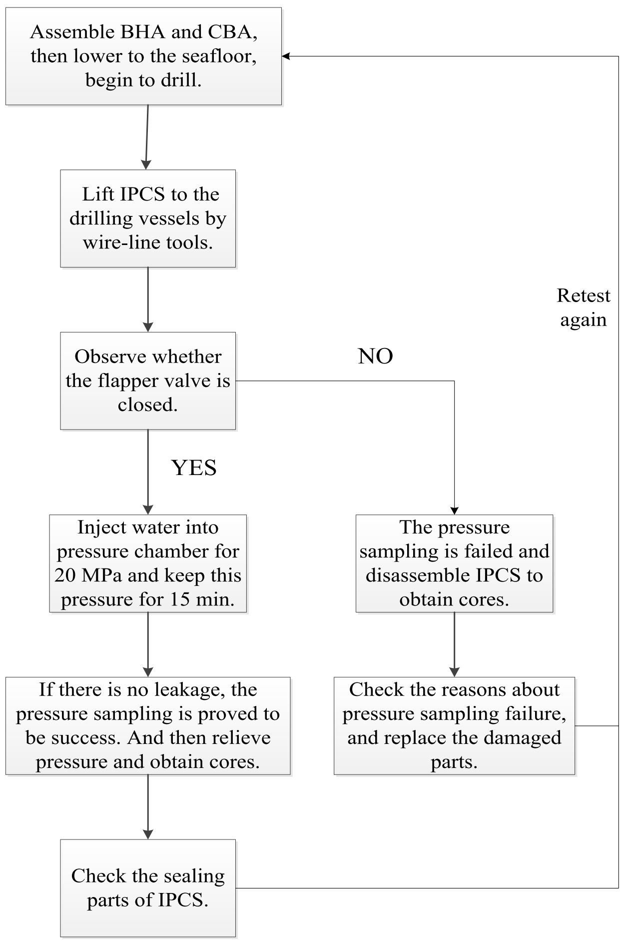

Figure 5. Offshore drilling experiment processes of the IPCS.

4. CONCLUSIONS

In this study, we presented the design method and experiments for a PCS for marine hydrates. The results obtained from

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Table 5. IPCS Drilling Parameters and Experiment Results

drilling location	drilling parameters	coring depth	core runs	success rate of the pressure core (%)	test pressure (MPa)	average core recovery (%)
offshore no. 1: the yellow sea of China	rotation speed: 60−90 rpm	seawater depth: 60 m, drilling depth: 20−22 m	2	100	20	80
	WOB: 1.5−2 T					
	drilling fluid displacement: 100−150 L/min					
offshore no. 2: the South China sea	rotation speed: 60−90 rpm	seawater depth: 43 m, drilling depth: 15.4−19.8 m	3	66.7	20	82.5
	WOB: 1.5−3 T					
	drilling fluid displacement: 120−200 L/min					
offshore no. 3: the South China sea	rotation speed: 70−90 rpm	seawater depth:39.8 m, drilling depth: 45.5−51.2 m	3	100	20	85.4
	WOB: 1.5−2.5 T					
	drilling fluid displacement: 100−250 L/min					

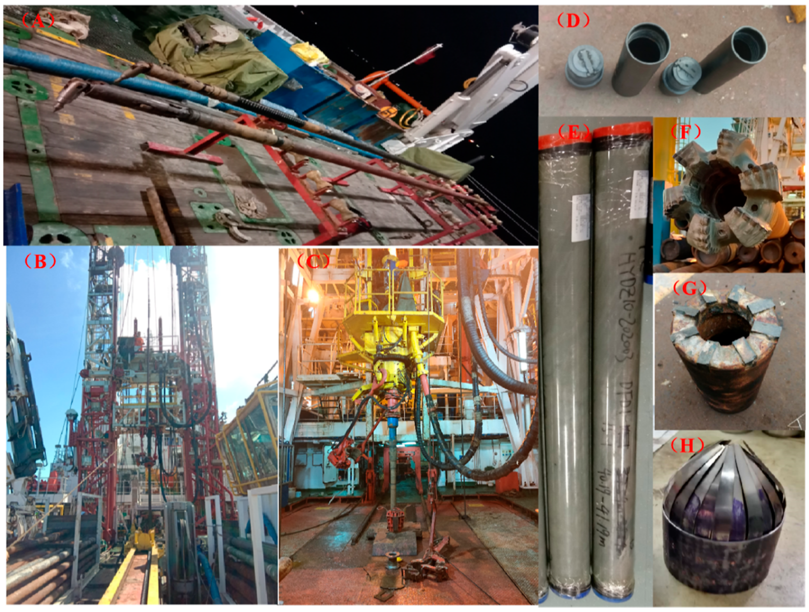

Figure 6. Offshore drilling experiments of the IPCS. (A) IPCS on the drilling vessel; (B) recovery of the CBA of the IPCS; (C) core drilling; (D) flapper valves; (E) cores from offshore drilling experiments; (F) outer core bit; (G) advanced core bit; (H) core catcher with many claws.

laboratory tests and drilling experiments verified that the pressure holding capacity, success rate of the pressure core, and core recovery of the IPCS were increased, improving the reliability of pressure sampling in unconsolidated strata. The key findings and conclusions were summarized as follows:

(1) This paper proposed a new structure for the PCS by a wire-line method to obtain hydrate cores. The flapper valve was chosen as the sealing component. Combined with a releasing subassembly, the flapper valve could close well, increasing sealing reliability of the PCS.

(2) Through pressure and temperature tests, the results showed that the IPCS had the ability to bear a pressure of 30 MPa and within 2 h, the pressure loss rate changed from 1.96% to 2.46%. Under the atmospheric temperature of 23.5 °C, the maximum temperature-rising value of cooled water in the pressure chamber was 0.96 °C in 2 h. This was beneficial to keep hydrated cores in stable conditions.

(3) In the offshore drilling experiments, the IPCS showed good performance. The pressure success rate reached 87.5% and the maximum core recovery was 85.4% in 8 core runs. These advancements will increase the efficiency of taking hydrate samples and provide higher-quality cores for geological and biological research studies of hydrate-bearing sediments under in situ conditions.

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Notes

The authors declare no competing financial interest.

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