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Development of applicable ice valves for ice-valve-based pressure corer employed in offshore pressure coring of gas hydrate-bearing sediments

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ABSTRACT

Because of sealing failures, less than 60% hydrate-bearing sediment pressure cores can be retrieved by pressure corers based on mechanical valves. The ice-valve-based pressure corer presents a promising solution to improve the recovery of pressurized hydrate-bearing sediment cores. This study aims to develop applicable ice valves for ice-valve-based pressure corer employed in offshore pressure coring of gas hydrate-bearing sediments. The pressure sustaining performance of the ice valves formed from both seawater and seawater mixed with bentonite were studied. Experimental results indicate that ice valves formed from pure seawater can sustain the pressure of only 3.2 MPa, which is far from meeting the requirement of pressure coring. By analyzing the freezing-equilibrium relationships in seawater, it can be concluded that there was a unfrozen zone containing calcium and magnesium ions kept in the axial center of the ice valve, which was considered to be the primary reason for the poor pressure sustaining capacity of sea ice valves. In addition, pressurizing tests of the ice valves made from seawater with different mass concentration of bentonite added were carried out and results showed that the sustained pressure can be greater than 38 MPa when the bentonite mass concentration was more than 5%, which was quite satisfactory for offshore pressure coring. Comprehensive analysis for the significant improvement of sustained pressure was also provided which reasonably and satisfactorily revealed the enhancement mechanism of bentonite on sea ice valves.

1. Introduction

Natural gas hydrates dispersed widely in permafrost regions and beneath of the sea in sediments of outer continental margins are considered as one the most promising and alternative future energy resource due to the advantages of large reserve, high energy density, widespread distribution and shallow buried depth (Makogon et al., 2007; Makogon,

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2010; Sloan and Koh, 2007). Sufficient and high-quality coring samples of hydrate-bearing sediments are crucial to advancing our understanding of formation, evolution and the potential exploitation of the natural gas hydrate environment and are essential for assessing the nature, distribution and concentration of natural gas hydrates (Timothy et al., 2011). Gas-hydrate-bearing sediments sampled by non-pressure coring techniques are often end up with highly disturbed samples due to the dissociation of gas hydrate and the exsolution of gas during recovery (Lee et al., 2013; Paull and Ussler, 2000). Pressure coring techniques eliminate or at least alleviate these affects enabling samples recovered to be relatively undisturbed and suitable for detailed examination (Schultheiss et al., 2008). Therefore, samples retrieved and analyzed at full in situ pressures are the “gold standard”, playing an important role in natural gas hydrate investigation, and can provide unique ground-truth data for geological, geotechnical, geochemical and microbiological testing and analyses (Dai et al., 2012; Stern et al., 2011; Kneafsey et al., 2011).

Pressure coring technique has been deployed successfully and refined continuously over the past decades. The famous pressure corers in use include the pressure core barrels (PCB) used in the Deep Sea Drilling Project (DSDP) (Peterson, 1984), the Pressure Core Sampler (PCS) used in Ocean Drilling Project (ODP) (Pettigrew, 1992), the Fugro Pressure Corer (FPC) and the HYACE Rotary Pressure Corer (HRC) developed in the EU-funded HYACE/HYACINTH programs (Schultheiss et al., 2009), the Pressure Temperature Core Sampler (PTCS) and the hybrid-PCS developed by Japan (Kawasaki et al., 2006; Kubo et al., 2014). These pressure corers trap pressurized core samples inside a sample autoclave by the use of a hydraulically actuated ball valve or flapper valve. However, in more than thirty percent of hydrate-bearing sediments samples retrieved by current pressure corers, no pressures or only partially in situ pressures are retained (Collett et al., 2006; Lee et al., 2013; Riedel et al., 2006; Shipboard Scientific Party, 2002; Yamamoto et al., 2012). This is attributed to failures of the mechanical valve for closing the lower end of a pressure corer (Shipboard Scientific Party, 2002). Such a mechanical valve works in the fluids laden with abundant solid particles in the borehole drilled. Its sealing performance can be easily deteriorated by the solid particles and drilling cuttings (Frith and Scott, 1993).

Significant scientific achievements have been obtained with the help of pressure corers based on mechanical valves mentioned above, which are however still far from being perfect owing to the low successful rate of pressure coring and high cost of deployment. By using the technique of pipe freezing or freeze-sealing which is used to isolate sections of a liquid filled pipeline by freezing the contents to form a solid plug (Richardson et al., 2003; Stone et al., 2004), Luo et al. (2015) proposed an ice-valve-based pressure-coring system, as shown in Fig. 1, using an ice valve made in situ from the drilling fluid in the borehole drilled to retain pressure, which is a promising solution to develop the new generation of pressure corers with high performance for investigating natural gas hydrates. Experimental results of Luo et al. (2015) show that the ice valves made from the pure drilling fluid (used in the Scientific Drilling Project of Gas Hydrate in permafrost regions of Qilian Mountains) can retain the pressure of up to 40 MPa without leakage, which means more than 6 times of safe factor compared to the maximum in situ pressure (less than 6 MPa) of the permafrost stratum in Qilian Mountain. Therefore, the ice-valve-based pressure coring technique has good application prospects in the permafrost drilling for Gas-hydrate-bearing sediments. However, unlike the drilling fluid used in the drilling of permafrost sediments, in the normal offshore drilling for natural gas hydrates sediments, conventional drilling fluid with various treatment agents will be severely restricted to minimize the pollution to marine environment, seawater will thus be the primary drilling fluid. Besides, there will also be occasions, adding bentonite to seal permeable stratums, enhance the removal of cuttings and maintain well bore stability (Jiang et al., 2011; Metcalf and Eddy, 2008). In this paper, the formation process of the pure sea ice valves and their pressure sustaining capacity will be discussed and the internal structures of the sea ice valves will be observed, and moreover, the ice valves made out of pure seawater with adding a certain amount of bentonite will be formed to see their performance of pressure retaining.

2. Lab apparatus and experimental procedure

As shown in Fig. 2, the specially designed device for this experimental research, mainly consists of an ice valve tube, an outer tube, a top end cap and a bottom end cap. Four screws were used to fasten the device to a workbench. A small hole is designed at the center of the top end cap to inject compressed air and to install a video endoscope through this small hole in the freezing process. The nominal diameter of the ice valve tube is 58 mm. Several annular grooves are evenly distributed along axial direction of the inner wall of the ice valve tube with the depth of 2 mm. The cone angle of the upper and lower conical surfaces of each annular groove is 60°. Two cryogenic coolant passages which connect to the spiral circulating passage setting in the outer tube are welded on the out surface of the outer tube. The experimental procedure can be divided into two steps, the freezing step and pressurizing step.

In the freezing step, a hypothermal thermostatic bath is employed to cool the cryogenic coolant at a set temperature with an error of ±0.5 °C. The bottom end cap is employed to block the bottom exit of the ice valve tube before the seawater with a measured volume is input into the ice valve tube. After inputting the seawater, the cryogenic coolant is pumped into the spiral circulating passage between the ice valve tube and the outer tube through the lower input passage to chill the seawater inside the ice valve tube. An insulating plate is fixed between the bottom end of the ice valve tube and workbench to reduce undesirable heat exchange, besides an 8 mm heat insulation cotton package is employed to serve as an thermal insulation coat for the experimental device. In addition, an endoscope is employed to monitor the formation process of the sea ice valves. The freezing step is followed by the pressurizing step. In the pressurizing step, a booster pump driven by an air compressor with a nominal input pressure of 0.8 MPa is employed to test the sealing performance of the ice valves and the nominal output pressure of the booster pump is 100 MPa. At this step, the bottom end cap is removed and the exhaust joint is installed after the ice valve was formed to monitor air leakage from the bubbling in a bucket full of water and then the pressure gauge is recorded to assess the sustained pressure capacity of the ice valve.