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Design and Failure Mechanism Analysis of Fire Resistance Test for Fire-Resistant Oil Booms

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Abstract. Fire-resistant oil boom is a special equipment used for emergency response to marine oil spill accidents. Its core function is to intercept floating oil while resisting high-temperature flames, preventing the spread of fire and oil pollution, and ensuring marine environmental safety. To verify the fire resistance performance of fire-resistant oil booms in actual fire environments, it is necessary to conduct continuous fire resistance tests to evaluate their structural integrity, thermal insulation efficiency, and flame retardancy. Based on standard fire resistance test requirements, this study designed and built a land-based water tank simulation test environment. The test site layout, flame loading method, temperature monitoring point arrangement, and data collection method were elaborated in detail, and the deformation, ablation, and failure processes of the oil boom under high-temperature combustion were systematically recorded. The test results show that the fire-resistant oil boom can still maintain key performance indicators in line with specification requirements under long-term flame action, verifying its fire resistance reliability. This study realizes the fire resistance test of fire-resistant oil booms under land-based water tank conditions for the first time, solving the problems of high cost and uncontrollability of marine tests. Meanwhile, through multi-parameter data monitoring, it provides data support for material optimization and failure mechanism analysis of fire-resistant oil booms, which has important reference value for improving marine oil spill fire emergency equipment.

Keywords: fire-resistant oil boom, fire resistance test, failure mechanism

1. Introduction

In recent years, with the rapid development of offshore oil exploration, development, and transportation industries, marine oil spill accidents have occurred frequently, posing serious threats to the marine ecological environment and economic development. The 2010 "Deepwater Horizon" drilling platform explosion in the Gulf of Mexico resulted in the leakage of approximately 4.9 million barrels of crude oil, polluting a sea area of more than 18,000 square kilometers [1]. In the same year, the "7·16" oil pipeline explosion and fire accident in Dalian, China, caused more than 1,500 tons of crude oil to flow into the sea, exerting long-term impacts on the ecological environment of the Bohai Bay [2]. These major accidents highlight the importance of marine oil spill prevention and control equipment. In particular, as a key emergency device, the performance of

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fire-resistant oil booms is directly related to the prevention and control effect of marine fires. Fire-resistant oil booms are mainly used to intercept oil spills and block the spread of flames, playing an irreplaceable role in emergency disposal of oil spill fires [3,4]. However, there are still many uncertainties in the performance of existing fire-resistant oil booms in actual fire environments, which need to be systematically evaluated and indexed through scientific tests.

China's current national standard GB/T 34621—2017 Fire-Resistant Oil Booms stipulates that products only need to pass a 30-minute fire resistance test, which is significantly different from the duration of actual marine fires. Large-scale oil spill fires often last for hours or even longer, and short-term fire resistance tests are difficult to truly reflect the practical performance of fire-resistant oil booms [5,6]. To accurately evaluate the performance of fire-resistant oil booms under long-term fire conditions, more stringent fire resistance tests must be carried out. However, offshore field tests face many challenges, such as high test costs, uncontrollable environmental conditions, high safety risks, and difficulty in achieving repeated tests and data collection. To address these issues, this study innovatively proposes a land-based water tank simulation test scheme. By constructing a controllable test environment, it realizes the accurate simulation of marine oil spill fires, providing a reliable platform for the performance testing of fire-resistant oil booms.

Relevant domestic and foreign standards put forward specific requirements for the fire resistance test of fire-resistant oil booms. According to GB/T 34621—2017 Fire-Resistant Oil Booms, the test requires forming the fire-resistant oil boom sample into a ring, polygon, or triangle, injecting test oil with a thickness of not less than 20mm inside and igniting it, maintaining combustion for 30 minutes. The standard clearly requires that the above-water part of the fire-resistant oil boom must withstand high temperatures above 1000℃, metal components shall not have obvious deformation after the test, and the underwater skirt and flexible section shall remain intact. The American Society for Testing and Materials (ASTM) standard ASTM F2152 Fire-Resistant Boom stipulates that fire-resistant oil booms shall be able to withstand direct flame exposure with an average heat flux of not less than $100kW/m^2$. These standards provide a basic basis for the performance evaluation of fire-resistant oil booms, but there are obvious deficiencies in long-term fire resistance tests, especially the lack of relevant specifications for the test environment of fire-resistant oil booms.

Based on the existing standard framework, this study focuses on the research on continuous combustion tests of fire-resistant oil booms. Firstly, a test water tank system is designed and constructed to realize the accurate simulation of the marine environment. Then, the collection of key parameters such as the structure, temperature, and heat flux of the fire-resistant oil boom is carried out. Finally, the failure mechanism of the fire-resistant oil boom under long-term high-temperature action is analyzed. This study aims to verify the performance of the fire-resistant oil boom under 24-hour continuous combustion at 1000°C through land-based water tank simulation tests. The research not only fills the gap in long-term onshore tests of fire-resistant oil booms but also provides a theoretical basis for product improvement by revealing its failure mechanism. This study will provide important references for the design optimization, standard revision, and engineering application of fire-resistant oil booms, and is of great significance for improving China's marine oil spill fire prevention and control capabilities.

2. Fire-resistant oil boom and test indicators

Fire-resistant oil boom is an emergency device specially designed for water surface oil spill response. In addition to the oil spill interception function of conventional oil booms, its prominent feature is the integration of fire and flame retardant properties. The floating body of the fire-resistant oil boom can withstand high temperatures up to 1000℃, and the skirt is generally made of special

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flame-retardant polymers, which are durable and can be repeatedly deployed. It can cope with oil spill fires that may occur in high-risk areas such as oil ports and terminals, providing a key physical barrier for fire fighting operations and pollution control.

The fire-resistant oil boom designed in this project adopts an innovative built-in float structure, mainly composed of above-water fire-resistant boom body, fire-resistant floats, high-strength steel wire ropes, underwater flame-retardant rubber skirts, counterweight anchor chains, and connecting splints. The above-water fire-resistant boom body is made of special high-temperature resistant materials, including alloy mesh and fiber felt, as shown in Figures 1 and 2. The built-in fire-resistant floats are made of heat-resistant steel or ceramic composite materials, which not only provide stable buoyancy but also maintain structural integrity under long-term flame exposure. A single section of the oil boom is designed as a standard 7-meter length, and both ends are quickly and reliably butted using high-strength connecting splints, which is easy for large-scale deployment and recovery.

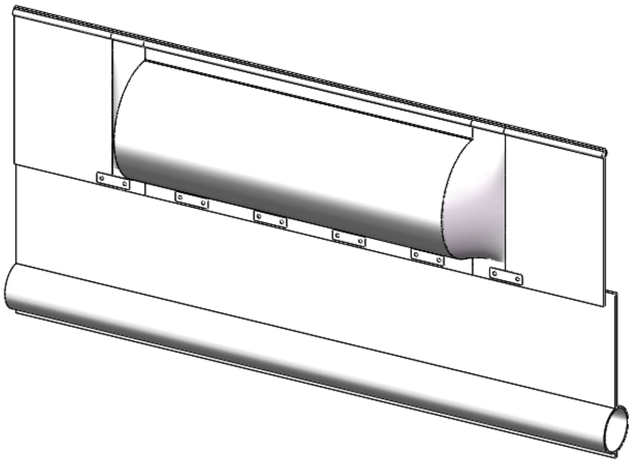

Figure 1. Design scheme diagram of fire-resistant oil boom

Figure 2. Product diagram of fire-resistant oil boom

Based on the requirements of the national standard GB/T 34621—2017 Oil Containment Booms and the American Society for Testing and Materials standard ASTM F2152 Fire-Resistant Boom, the key test indicators of the fire-resistant oil boom in this study are determined. GB/T 34621—2017 requires that during the 30-minute fire resistance test, the above-water part of the fire-resistant oil boom shall withstand high temperatures above 1000 ℃, metal parts shall have no obvious deformation, the underwater skirt and flexible section shall remain intact, and the fire-resistant coating is allowed to be partially burned without affecting the main structure. Meanwhile, ASTM

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F2152 stipulates that fire-resistant oil booms shall be able to withstand direct flame exposure with an average heat flux of not less than 100 kW/m². Based on the above standards, this study further expands the test indicators, including fire resistance performance under 24-hour continuous combustion conditions, heat flux distribution, structural deformation, tensile strength retention rate, and high-temperature stability of materials, to comprehensively evaluate the applicability of fire-resistant oil booms in extreme fire environments. The specific test indicators are shown in Table 1. The test also refers to the requirements of GB/T 36148.2-2018 for the strength and performance of oil booms to ensure that the test results meet both international and domestic standards.

Table 1. Test indicators of fire-resistant oil boom

Test Item	Standard Indicator
Platform Performance	Test combustion temperature (1000°C)
	Test heat flux (average 100kW/m²)
Fire Resistance Performance of Fire-Resistant Oil Boom	Above-water part withstands high temperature of 1000°C for 24h
Overall Performance of Oil Boom Belt	Total height
	Above-water height (freeboard)
	Underwater depth (draft)
	Buoyancy-weight ratio
	Tensile strength
Changes in Overall Performance of Belt After Combustion	Metal parts shall have no obvious deformation, and the underwater skirt and flexible section shall be intact
	PVC coating may be burned or peeled off, but shall not damage the main structure of the fire-resistant oil boom
	Above-water height (freeboard) ≥ 50% of the original freeboard
	Buoyancy-weight ratio ≥ 50% of the original buoyancy-weight ratio
	Tensile strength ≥ 50% of the original tensile strength

3. Test design of fire-resistant oil boom

3.1. Test environment

The fire resistance test of this study is carried out in an open-air site. The test environment is strictly controlled within the temperature range of 0°C~30°C to ensure that the test conditions are consistent with the actual application environment. During the test, the wind speed does not exceed 3.3m/s (equivalent to level 2 wind) to avoid significant impacts of wind on flame shape and heat transfer process. Meanwhile, the test is conducted in weather conditions without rain, snow, fog, or other precipitation to ensure that the test process is not disturbed by weather factors. The test environment design of the fire-resistant oil boom not only meets the requirements of standard specifications but also can truly simulate the marine environmental conditions that the fire-resistant oil boom may face in actual application, providing a guarantee for obtaining reliable test data.

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3.2. Test platform design

This study designs and constructs a land-based water tank test system, which can provide a safe and controllable 24-hour fire resistance test environment for fire-resistant oil booms. By simulating real marine environmental conditions, the test water tank system overcomes the shortcomings of high cost, high risk, and non-repeatability of offshore tests. It can realize the precise control of test conditions, including flame intensity, combustion time, and environmental parameters, ensuring the reliability of test data. Meanwhile, the land-based water tank test system is convenient for installing various monitoring equipment, which can comprehensively record the changes of key parameters such as deformation and temperature distribution of the fire-resistant oil boom under high-temperature action, providing data support for the study of failure mechanisms. In addition, onshore tests have the advantages of controllable cost and low safety risk, which are conducive to carrying out multi-condition comparative tests.

The design of the test water tank system takes meeting the requirements of 24-hour continuous combustion tests as the starting point, focusing on test safety, environmental simulation authenticity, and parameter controllability. The test site is selected in an open and flat area, with no flammable materials such as buildings and trees within 15 meters around, and a safety cordon is set up.

The test water tank system is mainly composed of a test water tank and a fire-spraying device, as shown in Figure 3. The test water tank adopts a 4m×4m×1.3m steel structure design with a refractory lining, which can accommodate a 7-meter-long oil boom to form a circular arrangement. The test water tank can accurately control the water level, equipped with a water level scale, automatic water supply pipeline, and regulating valve to ensure stable water level during the test. The fire-spraying device adopts a circular array arrangement of 24 special combustion nozzles. Each nozzle is connected to a propane gas source through a pressure-resistant gas pipe and equipped with an independent control valve. The nozzles are provided with group control valves in groups of 6, and 24 nozzles are equipped with a main control valve to realize the graded regulation of combustion intensity. All nozzles are installed on a three-dimensional adjustable bracket, which can accurately adjust the height, angle, and horizontal distance from the oil boom.

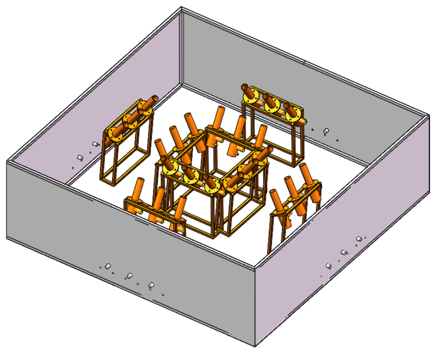

Figure 3. Design scheme diagram of test water tank system

The test water tank system is equipped with multiple safety protection measures, including a flame monitoring and automatic flameout device, a gas leakage alarm system, an emergency cooling device, and a remote monitoring system. The design not only meets the requirements of GB/T 34621-2017 but also can accurately simulate actual fire scenarios, providing a scientific and reliable test environment for the evaluation of oil boom fire resistance performance.

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4. Combustion test of fire-resistant oil boom

4.1. Pre-test preparation

Pre-test preparation for the fire-resistant oil boom combustion test is a key link to ensure the smooth progress of the fire resistance test, mainly including six aspects of work, as shown in Figure 4. Pre-test preparation is not only related to the safety of the test but also directly affects the accuracy and reliability of test data.

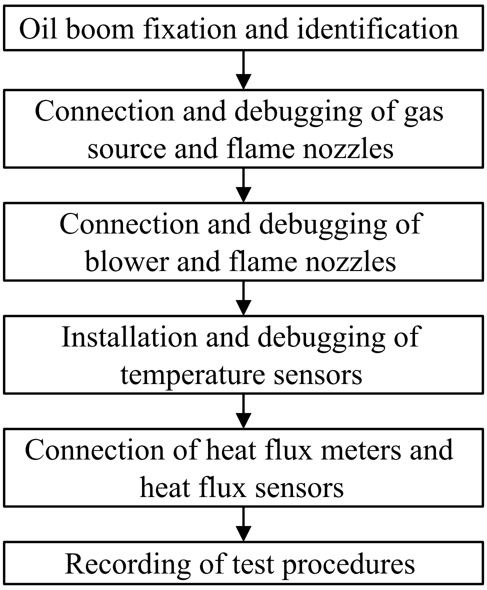

Figure 4. Flow chart of pre-test preparation

(1) Fixation and Identification of Oil Boom

Place the fire-resistant oil boom sample into the test water tank system, as shown in Figures 5 and 6, and fix it into a square-like shape according to the predetermined scheme. After fixation, measure the above-water and underwater heights of the sample in the water and record the data. To facilitate test operation and data recording, systematically number all floats and flame nozzles. At the same time, complete the connection and fixation of all test equipment, including gas pipe connection and sensor installation, to ensure that all systems are in place.

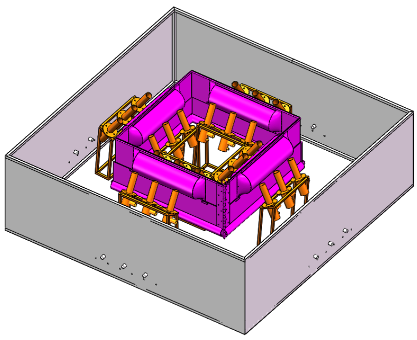

Figure 5. Schematic diagram of combustion test platform connection

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Figure 6. Fire-resistant oil boom placed in the test water tank

(2) Connection and Commissioning of Propane Gas Source and Flame Nozzles

Each flame nozzle is independently connected to a numbered corresponding propane gas source using a special gas pipe, and a safety pressure relief valve is installed at the gas source end. During commissioning, test each nozzle in numerical order, observe the combustion state and check the tightness of the pipeline, close the gas source after confirmation, and test other nozzles in turn. This process must ensure that all nozzles can burn normally without air leakage. If abnormalities are found during commissioning, immediately close the gas source for troubleshooting, and ensure that all nozzles reach the normal working state before conducting the formal test.

(3) Connection and Commissioning of Blower and Flame Nozzles

A blower is used to supply air to the flame nozzles. Each blower is connected to two nozzles at opposite positions through PVC steel wire pipes. During commissioning, start each blower in numerical order to test the air supply of the corresponding nozzles. After testing one blower, close it and then test the next one until all blowers pass the test. This commissioning process ensures the normal operation of the air supply system, provides a stable combustion-supporting air flow for flame combustion, and ensures the stability of the flame state during the test.

(4) Installation and Commissioning of Temperature Sensors

Install temperature sensors at key positions, and connect all sensors to the multi-channel temperature recorder in corresponding numbers. During commissioning, check the signal transmission of each channel to ensure that the temperature data can be accurately displayed in the recording software. Troubleshoot and debug channels with abnormal displays until all sensor data collection is normal.

(5) Connection of Heat Flux Meter and Heat Flux Sensor

Correctly connect the mobile heat flux sensor to the heat flux meter, and debug to ensure normal display of the equipment. Since the heat flux sensor is not suitable for long-term exposure to high-temperature environments, this test adopts an intermittent measurement method, with heat flux tests conducted once per hour. This setting can protect the equipment while obtaining heat flux data at key time periods, providing a basis for analyzing whether the heat flux of the oil boom meets the standard requirements.

(6) Test Process Recording

Establish a complete test recording system, including assigning special personnel to record key operations during the test; regularly recording test data such as temperature and heat flux; and video recording the test phenomenon throughout the process. The recording work runs through the whole process before, during, and after the test to ensure the completeness of test data and provide detailed basis for subsequent analysis.

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4.2. Combustion test

Before the start of the test, to ensure ignition safety, first start the blower system to pass air into all flame nozzles for 3~5 minutes to completely remove the propane gas that may remain in the pipeline. The ignition process is strictly carried out in numerical order, starting from the first nozzle and igniting each one at intervals of 30 seconds until all nozzles are successfully ignited. After ignition, start the blowers in turn to provide combustion-supporting air, and at the same time, real-time monitor the temperature change on the temperature sensor recorder, and adjust the sensors with abnormal displays. After the system operates stably, record the initial temperature, heat flux, and other basic data as the test reference values. This ignition procedure not only ensures test safety but also provides reliable initial conditions for subsequent data collection. Figure 7 shows the fire-resistant oil boom undergoing combustion test.

Figure 7. Fire-resistant oil boom under test

During the test, a comprehensive multi-parameter monitoring system is established. Temperature sensors continuously record the temperature changes at various key parts, and the data is automatically stored in the computer system. The mobile heat flux sensor is used to measure the heat flux value every hour, and detailed records are made. Pause the combustion every 2 hours for system inspection, measure the above-water height of the oil boom, observe the surface damage of the fire-resistant oil boom, check the deformation degree of its metal components and the integrity of the underwater skirt, and strictly control the fire stop time within 1 hour. At the same time, check the water level of the test water tank system every 30 minutes, and immediately replenish water to the design height if a drop is found.

4.3. Post-test measurement

After completing the 24-hour continuous combustion, the test is terminated according to the standard procedure: first close all propane gas sources, turn off the blower system after the flame is completely extinguished, and finally remove the temperature sensor. The fire-resistant oil boom after the test is shown in Figure 8. Detect the parameters of the fire-resistant oil boom after the test, including accurately measuring the changes in above-water and underwater heights, changes in total length and total height dimensions, weight difference before and after combustion, and measuring the tensile strength using a tensile machine. Focus on checking the deformation degree of metal components, the integrity of the underwater skirt and flexible section, and compare and analyze with the indicators in Table 1. Among them, special attention should be paid to the integrity of the main structure during the test to ensure that even if the surface material of the fire-resistant oil boom is burned or peeled off, the main functional structure can still meet the service requirements. This

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complete detection and evaluation system provides an objective basis for judging the fire resistance performance of the oil boom and can also be used as a reference for product improvement.

Figure 8. Fire-resistant oil boom after test

5. Failure mechanism analysis of fire-resistant oil boom

After the 24-hour continuous combustion test, the fire-resistant oil boom shows obvious morphological changes. The outermost PVC coating on the above-water part has been completely ablated and disappeared, exposing the internal alloy mesh structure. Although the main structures of the alloy mesh and fiber felt maintain their original shapes, slight damages such as oxidation discoloration and local deformation appear on the surface. Mechanical performance tests show that the tensile strength of the sample after the test still maintains more than 70% of the original strength, the underwater skirt structure is basically intact, but the freeboard height is reduced. The morphological changes of the fire-resistant oil boom directly reflect the damage mode of the fire-resistant oil boom under extreme fire conditions, providing an important basis for the analysis of failure mechanisms. Based on the test results, the failure mechanism of the fire-resistant oil boom is analyzed as follows:

(1) Structural Strength Attenuation Caused by Long-Term High-Temperature Action

The 24-hour continuous combustion, which far exceeds the requirements of the national standard, causes cumulative damage to the body structure of the fire-resistant oil boom. In the high-temperature environment, the metal alloy mesh undergoes oxidation reaction, and the grain boundaries are weakened, leading to a decrease in material strength and toughness. The fire-resistant fiber felt undergoes sintering under long-term thermal radiation, resulting in a decrease in porosity and gradual deterioration of thermal insulation performance. This degradation of material performance directly leads to a decrease in the overall structural strength of the oil boom, which is more prone to deformation and damage under wave loads. Test data show that the tensile strength retention rate of the sample after combustion is about 70-75%, which still meets the service requirements, but the safety margin is significantly reduced.

(2) Thermally Induced Change Effect of Material Performance

Each component material of the fire-resistant oil boom undergoes complex physical and chemical changes during the combustion process. The PVC coating above the water surface decomposes completely at the beginning of the test, losing its protective function. The oxide layer on the surface of the alloy mesh thickens, which not only reduces the material strength but also changes its heat transfer characteristics. The binder in the fire-resistant fiber felt decomposes at high temperatures, leading to a decrease in interlayer bonding force. The nano-aerogel felt undergoes slight sintering

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under continuous high-temperature action. These changes in material performance collectively lead to the degradation of the overall performance of the oil boom. Especially under repeated thermal cycle conditions, material damage shows an accelerating trend.

(3) Functional Changes Caused by the Structure of Fire-Resistant Oil Boom

The inconsistency of thermal deformation of fire-resistant oil boom materials under long-term combustion leads to changes in the overall coordination of the structure. The connection part between the float and the boom body produces slight deformation under thermal stress, destroying the original buoyancy balance. The connection between the underwater skirt and the above-water part becomes a weak link, which changes first under the action of thermal-mechanical coupling. These structural designs cause changes in the freeboard height of the oil boom under extreme conditions, which may lose the key function of blocking the spread of oil pollution. The improved design of fire-resistant oil booms in the future needs to focus on optimizing the thermal deformation coordination and connection reliability between various components.

6. Summary

This study conducts a systematic research on the fire resistance performance and failure mechanism of fire-resistant oil booms. Firstly, based on standards such as GB/T 34621-2017 and ASTM F2152, a test system including key indicators such as fire resistance time, structure, temperature, and heat flux is established. Secondly, an innovative land-based water tank test system is designed, and the performance evolution process of the oil boom under high-temperature environment is recorded in detail through continuous combustion tests. Finally, the failure mechanisms such as material thermal damage and structural strength attenuation of the fire-resistant oil boom are analyzed in depth. The study finds that the complete ablation of the PVC coating, oxidation of the alloy mesh, and sintering of the fiber felt are the main failure forms, and the structural changes caused by design are the main reasons for functional changes. The study confirms that the land-based water tank test can effectively simulate the real fire environment, and the conclusions obtained provide an important basis for the material optimization and structural improvement of fire-resistant oil booms, which has important guiding significance for improving the performance of marine oil spill fire prevention and control equipment.

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