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Construction of Air Tightness Test System of Pressurized Water Reactor Containment

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Abstract

The containment vessel, also known as the "nuclear reactor containment vessel", is the building forming the outermost peripheral pressurized water reactor, which controls and limits the diffusion of radioactive substances from the reactor to protect the public from radioactive substances. Therefore, it is necessary to test and verify the air tightness of the reactor envelope structure. Under the same test condition (differential pressure), the leakage per unit size of a single leakage source is considered the same as the actual engineering. Based on the relevant standards, the paper selects the equipment, builds the experimental platform, and conducts the simulation test with the scale scale model, laying the foundation for the establishment of the actual engineering.

Keywords

Containment Vessel; Air Tightness Test; Leakage Air Volume; Indoor and Outdoor Pressure Difference.

1. Introduction

Under the background of the increasing scarcity of fossil energy in the world, the energy consumption structure of all countries in the world is accelerating to clean and low-carbon, and nuclear power is also the main direction of China's power structure adjustment in the future. The development of nuclear power has experienced ups and downs. The Three li Island nuclear power plant in the United States, Fukushima nuclear power plant in Japan and Chernobyl nuclear power plant in the Soviet Union have all suffered serious nuclear leaks, which eventually caused irreversible consequences. When a nuclear power accident occurs, the reactor containment can prevent radioactive materials from leaking to the outside world and is an important nuclear safety barrier. Therefore, the air tightness of the containment is an "important link" in the safe operation of nuclear power plants. The air tightness test of the containment vessel is required before the opening of nuclear power projects. The overall sealing of the containment vessel directly determines whether the safety barrier of the PWR nuclear power unit is complete. The containment leakage is mainly caused by concrete pores / cracks, mechanical / electrical penetrant leakage []. Based on the scale model of a nuclear power project, the paper analyzes the air tightness test system, including the test platform structure, test scheme, leakage calculation, example analysis, etc., to provide a certain reference for the future containment gas tightness research of nuclear power project.

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2. Experimental Bench Construction and Test Scheme

2.1 Construction of Experimental Bench

A test bench is mainly composed of concrete test room, equipment room, control room and outdoor refrigeration unit. In the concrete room, the control room mainly places the electric control cabinet, monitoring computer and other equipment, and the pressure device and measuring device are mainly placed in the equipment room. The size of the concrete room is 7m×6m×6m (length, width and height), the wall panel is 400mm, the roof thickness is 350mm, and the bottom plate is 450mm, in which the size of the double open air door is 4.8m×4.45m (width and height), and the single open air door size is 1.2m×2.3m (width and height). In order to measure the air tightness of the door and the small door or create the negative pressure of the external wall, the sealing cover is arranged around the small door. The overall effect drawing is shown in Figure 1.

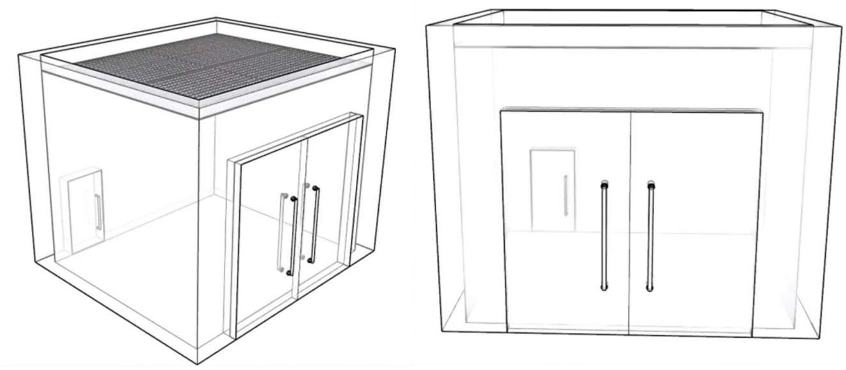

Figure 1. Overall effect diagram of the experimental bench

The model size, production, assembly process, installation process, concrete material, mixing ratio, production and construction technology, civil structure node, wall thickness, air pipe, pipe, cable penetration and hole plugging, to keep the plugging node consistent with the project according to the maximum size of the project. The length of door joint, concrete structure joint length, concrete wall or roof area relative to the actual engineering scale. Four pressure measuring points (about 1.2m on the ground) are located around the building and connected in series; 4 pressure measuring points are arranged inside the building, located in the middle and corner of the room (evenly above, middle and lower on height). In the later period, in order to measure the leakage of the small door of the gate, the pressure measuring point is reserved at the gate and the top, middle and bottom of the small door (evenly arranged on the height). The arrangement of the fixed pressure measuring points in the room is shown in Figure 1-2.

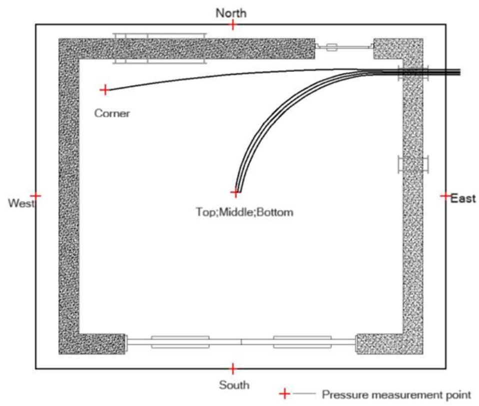

Figure 2. Layout drawing of the pressure measuring points

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2.2 Test Principle

The test bench sealing test is carried out according to NB / T 20018 of containment sealing test of PWR-2021 with the flow supplement method. The test method is conducted according to standard ISO9972-2015 and the uncertainty analysis reference standard ISO9972-2015 Appendix NC. The flow supplement test system can test the overall leakage, external door leakage and leakage of local parts. The principle of the test system is shown in Figure 1-2.

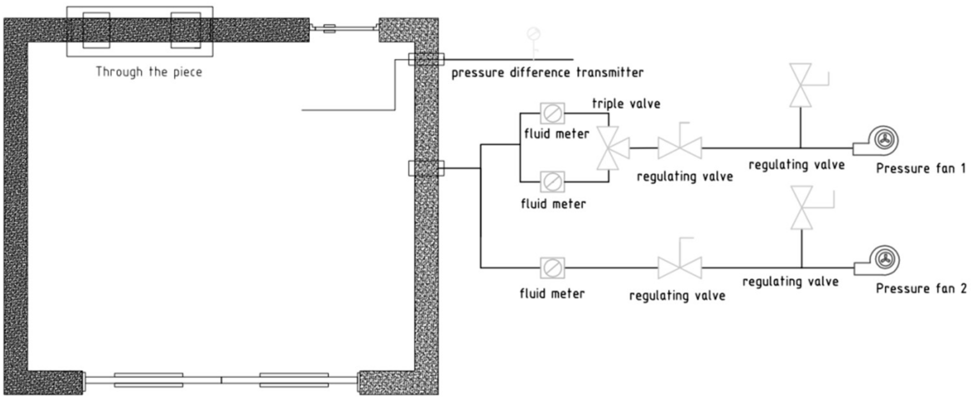

Figure 3. Schematic diagram of the test system

2.3 Preparation before the Test

(1) Inspection of the envelope structure

Check the closing of the outer door to ensure that the small door lock device and the movable threshold in place before testing; check the fixing of the penetration plate (rectangular 1800mm×800mm, circular DN450mm); and check the sealing plate in place.

(2) Instrument and equipment inspection

Before the use of instruments and equipment, ensure the normal operation of all instruments and equipment, the main inspection equipment is as follows: air treatment unit air valve and power fan, outdoor supporting cooling machine, pressure fan, flow meter (large, medium and small), differential pressure transmitter, temperature and humidity sensor, temperature sensor, atmospheric pressure sensor, etc.;

(3) Inspection of pipelines and valves

Check whether the pipeline is correctly connected, the pipeline is smooth, the adjustment valve is opened, the fan air supply and ventilation connection is correct.

2.4 Test Scheme

The whole test bench contains multiple leakage sources, so the sealing test should be divided into multiple steps to ensure the integrity of the test while minimizing the error, therefore, from the parts of the leakage, according to the size of the leakage, select the flow meter and differential pressure transmitter within the corresponding range, instrument measuring range as shown in Table 1, the specific test scheme is as follows:

Open the outer sealing cover of the large and small doors, close the penetration cover, close the outer door (see "three" before test), select the appropriate pressure fan and flow meter to the concrete room, the internal pressure measuring point and outdoor pressure measuring point are connected to the H and L interfaces of the differential pressure transmitter respectively. Adjust the frequency of the pressure fan 1 or the pressure fan 2 and the opening of the bypass control valve to stabilize the pressure of the room to the test requirements. The overall leakage amount of the room under the corresponding pressure in the corresponding time is recorded as Q1.

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On the basis of measuring Q1, reserve the sealing cover and cover vents on the outer side of the door, connect the measuring device and adjust the pressure fan to stabilize the pressure of the room to the experimental requirements, and that the overall leakage amount of the room under the corresponding pressure in the corresponding time is recorded as Q2.

On the basis of the completion of Q2 sealing measures, close the outer sealing cover and the cover plate of the small door (see "3. Preparation before test" for closing inspection), adjust the pressure fan to stabilize the room pressure to the requirements of the experiment, and that the overall leakage of the room under the corresponding pressure within the corresponding time is recorded as Q3.

On the basis of the completion of Q3 sealing measures, seal the connection of the engineering penetration parts 1,2,3 and the concrete parts, adjust the pressure fan to stabilize the room pressure to the experimental requirements, and get the overall leakage of the room under the corresponding pressure in the corresponding time is recorded as Q4.

Keep the above sealing measures unchanged, seal the two construction joints up and down of the whole concrete room, connect the measuring equipment, adjust the pressure fan to stabilize the room pressure to the experimental requirements, so that the overall leakage amount of the room under the corresponding pressure in the corresponding time is recorded as Q5.

After all sealing measures are taken, connect the measuring equipment, adjust the pressure fan to stabilize the room pressure to the experimental requirements, and get the overall leakage amount of the room under the corresponding pressure in the corresponding time is recorded as Q6.

According to the above test steps, the leakage amount of the leakage source can be found one by one, and the test and solution steps are shown in Figure 4.

Table 1. Equipment and list of experimental bench

Designation	Range ability	Remarks
Pressure fan 1	0~150m³/h	small flow rate high / low pressure operating conditions
Pressure fan 2	100~500m³/h	For high flow high / low pressure conditions
Pressure fan 3	0~1400m³/h	For wall wind pressure simulation conditions
Flow meter (small)	0.01~0.05m³/h	Penetration parts, construction joints and other small flow conditions
Flow meter (middle)	0.05~5m³/h	Often used in building structure and other small flow conditions
Flow meter (large)	5~500m³/h	Often used in the room / outer door high pressure, large flow operating conditions
Pressure difference transmitter 1~4	-2000Pa~2000Pa	For high-pressure operating conditions
Pressure difference transmitter 5	-600Pa~600Pa	For wall wind pressure simulation conditions
Pressure difference transmitter 6~9	-200Pa~200Pa	For low-pressure operating conditions

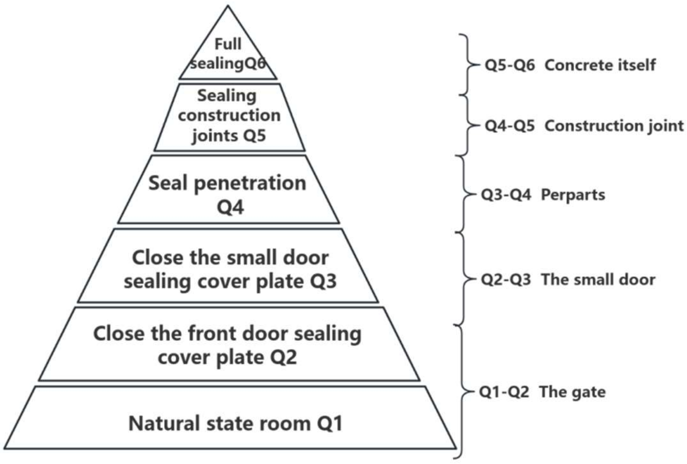

Figure 4. The overall test sequence

3. Containment Leakage Rate Calculation

At present, the United States is relatively mature in the study of containment sealing. Annex-2021 of NB/T 20018-2021. Based on the instrument configuration of this test bench, the flow supplement method in Appendix B is selected for testing. To verify the accuracy of the experimental data, the pressure drop method was applied for the same pressure difference range.

Air tightness requirements: leakage per unit gap length at 30Pa pressure difference, air leakage is less than 2.5 m³/(hm)

3.1 Flow Supplement Method

According to the target pressure of the room, the pressure measuring points including the target pressure are not less than 5 groups (all distributed), and test the pressure under the natural pressure difference of the leakage amount is calculated according to the following formula.

1) Post-pressure difference P calculation (considering the influence of natural pressure difference)

$$\Delta P = \Delta P_m - \frac{\Delta P_{0,1} + \Delta P_{0,2}}{2} \tag{1}$$

among:

$\Delta P_{0,1}$,$\Delta P_{0,2}$--Natural pressure difference before and after testing, Pa;

ΔP_m--Pressure for each measurement, Pa;

The leakage amount of each measured pressure (25°C,101.3KPa) is q, and the pressure and flow map are drawn according to the results of 5 sets of tests, and fitted according to formula (2), thus determining the airflow coefficient C and airflow index n.

$$q = C(\Delta P)^n \tag{2}$$

among:

C--Air flow coefficient

n --Airflow index;

It is suggested that the R2 value of the fitted curve should be no less than 0.98.The leakage at the target pressure can be obtained according to equation 2, e.g$q_{30} = C(30\text{Pa})^n$.

2) Uncertainty calculation

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The error of flow L per unit area is measured during negative pressure or positive pressure test; the total error (%) of leakage flow L can be calculated by the following equation:

$$s = \max(\sqrt{a^2 + b^2 + e^2}, d)$$

In the formula:

S--Percent of error of the leakage flow rate;

a--Percent of leakage flow error due to volume flow measurement error;

b--Percent error of leakage flow rate caused by building pressure measurement error;

d--Percent statistical error of leakage flow;

e--Percentage of leakage flow error due by density correction error.

4. Instance Validation

According to the above test scheme, the air tightness test of the whole room is conducted, and the good weather state is selected for the test. Before the test, the initial pressure difference and indoor and outdoor temperature are recorded, and the anemometer is used to measure the outdoor wind speed. Therefore, during the test, the outdoor surface wind speed is not more than 3 m/s or the meteorological wind speed is not more than 6 m/s.

Use the flow supplement method to measure the leakage, when the flow meter reading and pressure reading tend to stabilize, click the "data report" for data collection, select the current test condition, the flow meter and differential pressure transmitter, set the data collection interval, click from the beginning, the data report will automatically collect flow, pressure, temperature and humidity, atmospheric pressure and other parameters, click the export EXCEL after data acquisition, save the data.

4.1 Test Results

The potential leakage source in the whole building is measured step by step. When the overall leakage amount is large, the instantaneous flow value under the small pressure difference-30Pa can be measured by using the instrument, and the leakage amount of the corresponding part can be obtained after the working condition in the room is stable. When the door, small door closed, sealed cover plate and the reserved ventilation closed, the room air tightness, the final construction joints, penetration parts and concrete leakage is relatively small, the flow meter reading cannot be further measured, to measure the fitting curve and actual data, the pressure difference from 30Pa to 1500Pa, to measure the leakage of the whole room plugging. The measurements of the four groups are shown in Figure 3~6.

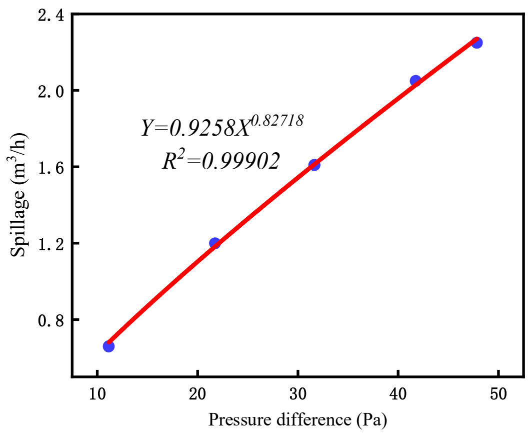

Figure 5. Overall Q1 of the natural room

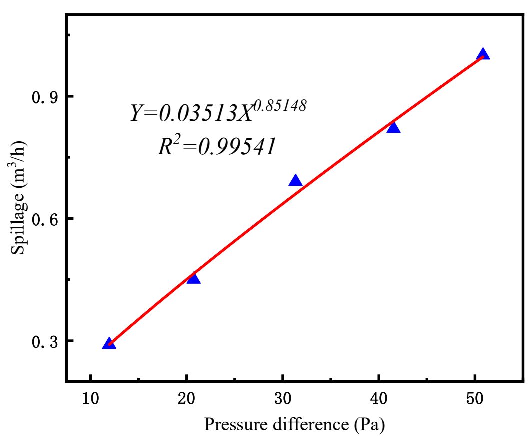

Figure 6. Close the gate Q2

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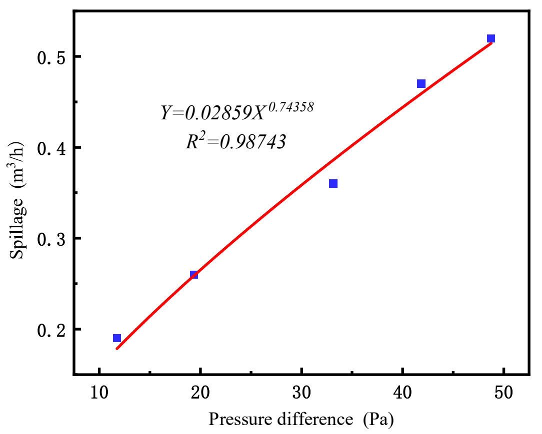

Figure 7. Closing the small door Q3

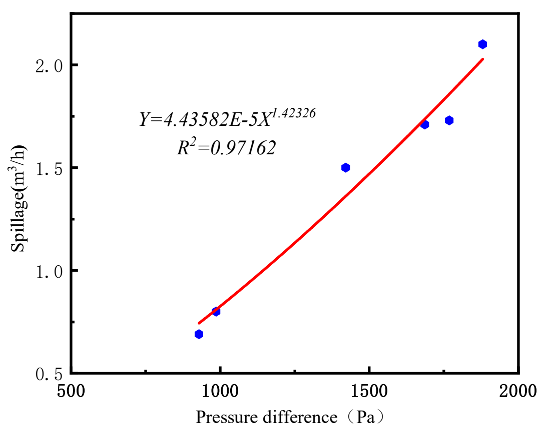

Figure 8. Close the penetration piece Q4

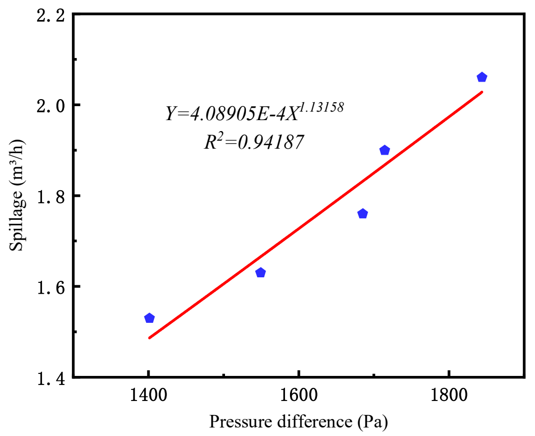

Figure 9. Close construction joint Q5

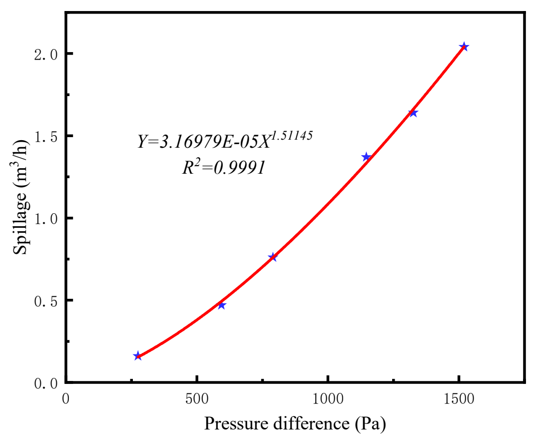

Figure 10. Closed room overall Q6

According to the test results, it is not difficult to see that the fitting degree of the test results after closing the construction joint and the penetration parts is low, so the measurement results of the two groups of data have large errors, the overall leakage of the measurement site and the measurement error of the instrument itself lead to the unsatisfactory of the two groups of data.Therefore, the subsequent test needs to replace the flowmeter with smaller range range and higher accuracy to measure the penetrations and construction joints of the concrete room. Through the above experimental results, it can be concluded that the air tightness requirement of the room without plugging: the leakage per unit gap length is under 30Pa pressure difference, and the air leakage is less than 2.5 m^3 / (h).

5. Conclusion

To sum up, the construction of the experimental system has large reference significance, but the existing test accuracy in a small range can have error, in the process of repeated pressure, the door deformation and corresponding sealing measures aging also have greater influence on the leakage, so need further research, wider test range, higher test accuracy of air tightness detection method, to meet the needs of future reactor concrete containment technology development.

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