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# Non-destructive Testing Techniques for Stress Analysis of Pressure Vessels

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## Abstract

Pressure vessels are critical industrial equipment used to store and transport high-pressure fluids or gases, and ensuring their safety is of utmost importance. Stress analysis is a crucial step in assessing the integrity of a vessel's structure to ensure it can withstand high-pressure conditions without failure. Nondestructive testing is important for stress analysis of pressure vessels. These technologies, such as ultrasonic, radiographic, and magnetic particle inspection, can detect potential cracks, corrosion, deformation, and other defects without causing damage to the container. Through regular non-destructive testing, operators can detect problems early and take measures to repair or replace equipment, thus avoiding potentially catastrophic accidents and production shutdowns. To effectively evaluate the working condition and remaining lifespan of a pressure vessel, stress analysis and non-destructive testing are required. By summarizing the basic principles and common methods of stress analysis for pressure vessels, this paper provides a systematic introduction to non-destructive testing technologies such as X-ray testing, ultrasonic testing, liquid penetration testing, and acoustic emission testing. It also discusses their specific applications in pressure vessels, analyzes the advantages and disadvantages of each technology, and examines their scope of application. It is hoped that this paper can promote the development of non-destructive testing technology for stress analysis of pressure vessels.

## Keywords

Pressure vessel, Stress analysis, Non-destructive testing, Technology application

## Introduction

A pressure vessel refers to a closed container that can withstand internal or external pressure and usually stores gas, liquid, or gas-liquid two-phase media inside. Pressure vessels are widely used in the petroleum, chemical industry, metallurgy, electric power, aviation, aerospace, and other fields, and are indispensable equipment in industrial production. However, because the pressure vessel will be affected by various loads, environmental factors, and material aging during use, its structure and performance will change, resulting in stress concentration, deformation, cracks, corrosion, and other defects, and then lead to an explosion, leakage, and other accidents, resulting in serious casualties and economic losses [1].

To ensure the safe operation of the pressure vessel and extend its service life, it is necessary to carry out regular or irregular inspections and evaluations. Stress analysis is an important means to evaluate the structural strength and stiffness of pressure vessels, and non-destructive testing is an effective method to find and locate the defects of pressure vessels. Stress analysis can be based on the working conditions of the pressure vessel, geometric shape, material properties, and other parameters to calculate its various stresses and deformation, and compared with the allowable value to determine whether it meets the strength and stability requirements. Non-destructive testing can use acoustic, optical, electrical, magnetic, and other physical characteristics, without damaging or affecting the performance of the tested object, detect its internal or surface defects, and give the location, size, shape, nature, and other information of the defect, to assess its quality and integrity.

This paper aims to summarize the basic principles and methods of stress analysis of pressure vessels, introduce the common nondestructive testing technology and its application in pressure vessels, analyze the advantages and disadvantages of each technology and the scope of application, and look forward to the development trend and prospect of nondestructive testing technology.

## 1. Basic principles and methods of stress analysis of pressure vessels

### 1.1 Basic principles of stress analysis of pressure vessels

The basic principle of stress analysis of pressure vessel is to establish the mathematical model of stress and deformation of pressure vessel according to the conditions of mechanical balance, material continuity, and deformation coordination, solve the stress and deformation distribution of pressure vessel under given working conditions, and compare it with the corresponding strength and stability criteria to determine whether it meets the design requirements [2].

The main purposes of pressure vessel stress analysis are as follows:

(1) Determine the structural size and material selection of the pressure vessel so that it has sufficient strength and stiffness to avoid over-design or under-design;

(2) To predict the stress concentration, deformation, fatigue, creep, and other phenomena that may occur during the use of pressure vessels, and to evaluate their impact on the life and safety of pressure vessels;

(3) Provide a theoretical basis for non-destructive testing, determine the testing scheme and testing parameters, and improve the testing efficiency and accuracy;

(4) Provide technical support for fault diagnosis and accident analysis, find out the cause and responsibility of the fault or accident, and propose improvement measures and prevention suggestions.

### 1.2 Common methods for stress analysis of pressure vessels

There are three commonly used methods for stress analysis of pressure vessels:

(1) Analytical method: Analytical method is the use of a mathematical formula to directly solve the pressure vessel stress and deformation method. It is suitable for simple shape, uniform material, regular load, and other conditions of the pressure vessel. The advantages of the analytical method are fast calculation speed, high precision, and intuitive results, but the disadvantages are that it can only deal with some special cases and can not consider the effects of complex boundary conditions, nonlinear factors, and actual working conditions.

(2) Numerical method: The numerical method is the use of a computer to discretize the pressure vessel, the continuous problem into a discrete problem, and then the numerical algorithm to solve the pressure vessel stress and deformation method. It is suitable for complex shapes, non-uniform material, irregular load, and other conditions of the pressure vessel. The advantage of the numerical method is that it can deal with various complex problems, consider various influencing factors, and simulate the actual working conditions. The disadvantage is that the calculation is large, and the accuracy is affected by the degree of discretization and the stability of the algorithm.

(3) Experimental method: The experimental method is the method of using a physical model or prototype to load the pressure vessel and measure its stress and deformation. It is suitable for verifying theoretical calculation results or studying problems that are difficult to solve using theoretical or numerical methods. The advantage of the experimental method is that it can directly reflect the real situation and provide reliable data, but the disadvantage is that it is time-consuming, costly, and limited by experimental conditions.

## 2. Common non-destructive testing technology and its application in pressure vessels

### 2.1 X-ray detection technology

X-ray testing technology is a non-destructive testing technology that uses the attenuation characteristics of rays (such as X-rays or gamma rays) in media of different densities to form images on sensitive materials, to show the internal structure and defects of the tested object. X-ray inspection technology has the following advantages:

It can detect various defects inside or on the surface of the pressure vessel, such as cracks, pores, inclusions, corrosion, etc.

The pressure vessel can be tested comprehensively or locally, and is not limited by the shape, size, material, etc.;

It can provide intuitive image records for easy analysis and judgment.

X-ray inspection technology also has the following disadvantages:

(1) It is necessary to use high-energy ray sources, which have certain hazards to operators and the environment, and strict protective measures need to be taken.

(2) Need to use professional equipment and personnel, high cost, low efficiency;

(3) The depth and direction of the defect cannot be measured directly, and quantitative analysis needs to be combined with other methods.

The application of X-ray detection technology in pressure vessels is mainly as follows:

(1) Radiography: Radiography is the method of placing the ray source on one side of the subject and the sensitive material (such as film) on the other side so that the ray passes through the subject and forms an image on the sensitive material. This method can clearly show the defects inside or on the surface of the tested object, but it requires a long time for post-processing such as film development and development [3].

(2) Real-time X-ray imaging method: The real-time X-ray imaging method involves positioning the ray source on one side of the object to be examined, while the image intensifier or digital detector is placed on the other side. This allows the ray to pass through the object and create a real-time image on the image intensifier or digital detector. This method allows for real-time observation and recording of defects inside or on the surface of the object. However, it requires the use of high-performance image processing equipment and software, resulting in high costs.

(3) Computed tomography: Computed tomography is a method of moving the ray source along the axis of the object to be examined, projecting it from different angles, and then using the computer to reconstruct the projection data to obtain the internal tomography images of the object to be examined at various levels. This method can accurately measure the density distribution and defect information of each level of the object, but it needs to use complex mathematical algorithms and a lot of computing resources, and the efficiency is low.

### 2.2 Ultrasonic detection technology

Ultrasonic testing technology is a non-destructive testing technology that uses the propagation characteristics of ultrasonic waves (sound waves with frequencies higher than 20kHz) in different media to form signals on the receiver, to reflect the internal structure and defects of the tested object. Ultrasonic testing technology has the following advantages:

(1) It can detect various defects inside or on the surface of the pressure vessel, such as cracks, pores, inclusions, corrosion, etc.;

(2) The pressure vessel can be tested comprehensively or locally, and is not limited by shape, size, material, etc.;

(3) It can provide direct signal recording for easy analysis and determination.

Ultrasonic testing technology also has the following shortcomings:

(1) Need to use professional equipment and personnel, high cost, low efficiency;

(2) Surface treatment of the tested object is required to ensure good acoustic coupling conditions;

(3) The shape and nature of the defect cannot be measured directly, so it needs to be combined with other methods for quantitative analysis.

The application of ultrasonic testing technology in pressure vessels is mainly as follows:

(1) Ultrasonic reflection method: The ultrasonic reflection method is to place the ultrasonic transmitter and receiver on the same side of the object under test so that the ultrasonic wave is reflected inside the object under test and forms a signal on the receiver. This method can detect the defects inside or on the surface of the object that is perpendicular or nearly perpendicular to the transmitting direction, but the detection effect is poor for the defects that are parallel or nearly parallel to the transmitting direction.

(2) Ultrasonic transmission method: The ultrasonic transmission method is to place the ultrasonic transmitter and receiver on both sides of the object under test so that the ultrasonic wave passes through the object under test and forms a signal on the receiver. This method can detect the defects parallel or nearly parallel to the transmitting direction inside or on the surface of the tested object, but the detection effect is poor for the defects perpendicular to the transmitting direction.

(3) Ultrasonic phased array method: The ultrasonic phased array method is a plurality of ultrasonic transmitters and receivers to form an array, by controlling the excitation timing and phase of each element, to achieve the ultrasonic beam focusing, scanning, and reconstruction, and form a signal on the receiver method. This method can realize the detection of defects in all directions and depths of the internal or surface of the tested object, with high sensitivity and high resolution, but it requires the use of high-performance electronic equipment and software, and the cost is high [4].

### 2.3 Liquid penetration detection technology

Liquid penetrant detection technology utilizes the capillary phenomenon. A liquid penetrant, which contains dye or a fluorescent agent, is applied to the surface of the tested object. This allows it to seep into any surface openings or defects. The excess penetrant is then removed using a remover. Finally, a developer is applied to the surface, which absorbs the penetrant and reveals the location and shape of the defect. A nondestructive testing technique that reveals defects in the surface openings of the tested object. Liquid penetration testing technology has the following advantages:

(1) It can detect various defects in the surface openings of pressure vessels, such as cracks, folding, intercalation, slag

inclusion, etc.;

(2) Any non-porous solid material can be tested, regardless of the pressure vessel shape, size, material, etc.;

(3) It can provide an intuitive defect display, easy to analyze and judge.

Liquid penetration testing technology also has the following disadvantages:

(1) Only the surface opening defects of the pressure vessel can be detected, but the internal or closed defects cannot be detected;

(2) Surface treatment of the tested object is required to remove oil, rust, oxide, etc.;

(3) The use of toxic or flammable chemical reagents is harmful to the operator and the environment, and safety measures must be taken.

The application of liquid penetration testing technology in pressure vessels is mainly as follows:

(1) Visible light dye penetration method: Visible light dye penetration method is the use of visible light dye (such as red or black) and white or gray developer, through the naked eye or magnifying glass to observe the defect display method. The method is simple and inexpensive but requires good lighting conditions and visual sensitivity.

(2) Fluorescent dye penetration method: Fluorescent dye penetration method is the use of fluorescent agents (such as yellow-green or orange-red) and colorless or pale developers, under ultraviolet or black light to observe the defect display method. The method is highly sensitive and can detect small defects, but requires special fluorescence equipment and dark room conditions.

(3) Fluorescent magnetic particle penetration method: The fluorescent magnetic particle penetration method is to coat the penetrant containing the fluorescent agent and magnetic particles (such as ferrite) on the surface of the subject, and add magnetic poles at both ends to form a closed magnetic circuit, and observe the defect display method under ultraviolet light or black light. This method combines the advantages of the fluorescent dye penetration method and magnetic particle detection method and can detect surface and near-surface defects at the same time, but it is only suitable for ferromagnetic materials.

### 2.4 Acoustic emission detection technology

Acoustic emission detection technology is a non-destructive testing technique that utilizes the pressure vessel to produce subtle acoustic signals, known as acoustic emission signals when the pressure vessel is exposed to external loads or internal stress variations. By receiving, amplifying, analyzing, and processing these signals, the stress state and defect information of the pressure vessel are reflected. Acoustic emission detection technology has the following advantages:

(1) It can detect various defects inside or on the surface of the pressure vessel, such as cracks, pores, inclusions, corrosion, etc.;

(2) The pressure vessel can be tested comprehensively or locally, and is not limited by shape, size, material, etc.;

(3) On-line testing can be carried out in the normal working state of the pressure vessel without stopping or unloading.

Acoustic emission detection technology also has the following shortcomings:

(1) It needs to use professional equipment and personnel, high cost, low efficiency;

(2) It is necessary to analyze and process acoustic emission signals to eliminate the influence of noise and interference;

(3) The location and size of defects cannot be measured directly, so quantitative analysis needs to be combined with other methods.

The application of acoustic emission detection technology in pressure vessels is mainly as follows:

(1) Acoustic emission detection in pressure vessel load test: Acoustic emission detection in pressure vessel load test is a method to monitor the acoustic emission activities of the pressure vessel under different loads and determine whether there are active defects or dangerous cracks when the pressure vessel is undergoing water pressure test or air pressure test. This method can effectively evaluate the safety performance and remaining life of the pressure vessel [5].

(2) Acoustic emission detection in the operation of pressure vessels: Acoustic emission detection in the operation of pressure vessels is a method to monitor the pressure vessel online by using a portable acoustic emission instrument during regular or irregular inspection, record its acoustic emission activities under working conditions, and determine whether there is abnormal change or potential danger. The method can detect and promptly warn of any failure or accident involving the pressure vessel.

(3) Acoustic emission detection in pressure vessel damage assessment: Acoustic emission detection is used in the assessment of damage in pressure vessels. It involves the use of a specialized acoustic emission instrument to conduct a thorough detection process before repairing or replacing a defective or damaged pressure vessel. This process helps determine the type, location, degree, and expansion trend of the defect or damage and enables the development of appropriate treatment plans and suggested methods. This method can scientifically guide the maintenance or replacement of pressure vessels.

## 3. Conclusion

Nondestructive testing (NDT) plays an important role in evaluating the working condition and remaining life of pressure vessels. All kinds of non-destructive testing technologies have certain advantages, but there are also some limitations. It is necessary to choose the most suitable technology according to the specific testing needs or use a variety of technologies. Looking forward to the future, with the improvement of testing equipment performance, the continuous emergence of new technologies, and the development of multi-technology integration, the non-destructive testing technology for pressure vessel stress analysis will evolve towards intelligence, refinement, and integration. The integration of non-destructive testing technology with digital image processing, artificial intelligence, and other high-tech advancements will enhance the accuracy and reliability of test results. It will also improve detection efficiency, providing robust support for quality control and safety monitoring of pressure vessels. The content of this paper can provide valuable insights for the development of nondestructive testing technology for stress analysis of pressure vessels.

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