OT-2026-000000055

Differential Pressure Leak Test with Adiabatic Settling Compensation

Published	September 15, 2026 at 11:54:45 UTC
Permanent URL	https://opentechnical.org/p/OT-2026-000000055
Classification	Manufacturing & Assembly Equipment > Test and Inspection > Leak Testing
Document SHA-256	2455a779326a2c37d7c9df4e20c003bb1f983c1deb9902f6bca875ecfcfadef9
Extent	2,684 words, 18 numbered paragraphs, 2 figures

Abstract

This disclosure describes an arrangement for leak testing sealed components using a differential pressure method that compensates for adiabatic pressure changes. The system employs a test volume and a reference volume, both pressurized simultaneously, and measures their pressure difference over time. By modeling the transient pressure effects caused by adiabatic compression or expansion during the fill phase, the system isolates pressure changes attributable solely to leakage. This compensation mechanism reduces the stabilization time typically required before measurement, thereby optimizing the test cycle while maintaining accuracy in identifying components that meet specified leak rate criteria.

1. Technical Field

[0001] The present disclosure relates to methods and apparatus for leak testing sealed components, particularly those employing pressure decay techniques to detect fluid communication between an internal volume and the external environment.

2. Technical Context

[0002] Pressure decay leak testing is a common method for verifying the integrity of sealed components. In a typical pressure decay test, a component's internal volume is pressurized, and a subsequent decrease in pressure over a defined period indicates a leak. A significant challenge in these tests arises from thermal effects. When a gas is rapidly compressed and introduced into a test volume, its temperature increases adiabatically. Conversely, as the gas expands during filling, it cools. This temperature change causes a corresponding pressure change, independent of any leakage, as the gas returns to thermal equilibrium with its surroundings. This phenomenon, often referred to as adiabatic settling, can obscure actual leak-induced pressure drops, requiring a prolonged stabilization period before accurate leak measurement can commence. If the stabilization period is insufficient, the residual adiabatic pressure change can lead to either false rejections (a good part appears to leak) or false passes (a leaking part's pressure drop is masked). The disclosed arrangement addresses this issue by compensating for these transient thermal effects, thereby enabling accurate measurement with reduced stabilization times.

3. System Overview

[0003] The described system employs a differential pressure leak testing method, where the pressure in a test volume (10) containing the component under scrutiny is compared against the pressure in a sealed reference volume (12). Both volumes are pressurized simultaneously from a common pressure source (14) through a fill valve manifold (18). A differential pressure sensor (16) continuously monitors the pressure difference between the test volume (10) and the reference volume (12). An absolute pressure sensor (26) and an ambient temperature sensor (28) provide additional environmental data to a system controller (22). The system controller (22) executes a specific test sequence, including a fill phase, a stabilization phase, and a measurement phase. During the stabilization phase, the system controller (22) applies a compensation model to account for the expected adiabatic pressure changes, allowing for earlier and more accurate detection of leak-induced pressure decay. A calibrated leak (24) is integrated to periodically verify the system's operational integrity and measurement accuracy. The overall system is depicted in FIG. 1, with a detailed view of the test and reference volume configuration shown in FIG. 2.

4. Components

[0004] The system incorporates several key components:

[0005]

- **Test Volume (10):** This is the internal volume of the component being tested. It is designed to be connectable to the pressure system and to maintain a sealed condition during the test, except for any leaks present in the component itself. The volume can range from 10 milliliters to several liters, depending on the component's size.
- **Reference Volume (12):** A sealed, rigid vessel with a known, stable internal volume. Its internal volume is typically sized to be similar to or slightly larger than the test volume (10) to minimize the impact of slight volume discrepancies on differential pressure measurements. It is constructed from a material with high thermal conductivity, such as aluminum, to facilitate rapid thermal equalization with the ambient environment.
- **Pressure Source (14):** A regulated supply of compressed gas, typically dry air, capable of delivering gas at a stable pressure within a range of 0.1 MPa to 1.0 MPa (1 to 10 bar). It includes appropriate filtration to prevent particulate contamination of the system.
- **Differential Pressure Sensor (16):** A transducer designed to measure the pressure difference between the test volume (10) and the reference volume (12). This sensor has a high sensitivity, capable of resolving pressure differences as small as 1 Pa (0.01 mbar), and a low hysteresis. Its output is an electrical signal, typically 0-10 V or 4-20 mA, proportional to the differential pressure, which is fed to the system controller (22).
- **Fill Valve Manifold (18):** This manifold comprises one or more pneumatically or electrically actuated valves (e.g., valve (18a) in FIG. 2) that control the flow of pressurized gas from the pressure source (14) into both the test volume (10) and the reference volume (12). The valves are selected for rapid response and minimal internal leakage.
- **Vent Valve Manifold (20):** Similar to the fill valve manifold (18), this manifold contains valves (e.g., valve (20a) in FIG. 2) for rapidly exhausting gas from the test volume (10) and the reference volume (12) to atmospheric pressure at the end of a test cycle.
- **System Controller (22):** A programmable logic controller (PLC) or industrial PC equipped with analog and digital I/O modules. It manages the entire test sequence, including valve actuation, data acquisition from sensors, application of the adiabatic settling compensation model, leak rate calculation, and pass/fail decision making.* **Absolute Pressure Sensor (26):** A transducer measuring the absolute pressure within either the test volume (10) or the reference volume (12), or a common point in the pneumatic circuit. This sensor typically has a range matched to the fill pressure, for example, 0 to 1.5 MPa, and provides a

precise measurement of the system's operating pressure, essential for accurate leak rate calculations and compensation modeling. It is shown in FIG. 2.

- **Ambient Temperature Sensor (28):** A high-resolution temperature sensor, such as a platinum resistance thermometer (Pt100), positioned to measure the ambient temperature surrounding the test setup. This data is critical for the adiabatic settling compensation model, providing the baseline temperature for thermal equilibrium. It is shown in FIG. 2.
- **Calibrated Leak (24):** A precisely manufactured component designed to exhibit a known, stable leak rate. It typically consists of a capillary tube or a porous element. This component can be selectively introduced into the test circuit (e.g., connected to the test volume (10) via an isolation valve) to simulate a leak and verify the system's accuracy and sensitivity.

5. Operation

[0006] The operation of the differential pressure leak testing system proceeds through a defined sequence, managed by the system controller (22).

[0007] **Start-up and Initialization:** Upon system activation, the system controller (22) performs a self-diagnostic check of all sensors and valves. The ambient temperature sensor (28) provides an initial ambient temperature reading, and the absolute pressure sensor (26) verifies that the system is at atmospheric pressure. The system controller (22) loads the test parameters, including fill pressure, stabilization time, measurement time, and acceptable leak rate thresholds.

[0008] **Test Cycle - Fill Phase:** With the component securely connected to the test port, the system controller (22) commands the fill valve manifold (18) to open, introducing pressurized gas from the pressure source (14) simultaneously into both the test volume (10) and the reference volume (12). This rapid pressurization causes adiabatic heating of the gas within both volumes. The fill phase continues until the absolute pressure sensor (26) confirms that the target fill pressure has been reached, typically within 1 to 5 seconds. During this phase, the differential pressure sensor (16) will register an initial transient difference, which rapidly diminishes as the pressures in both volumes equalize, assuming no initial leak.

[0009] **Test Cycle - Stabilization Phase (with Compensation):** Immediately after the fill valves close, the stabilization phase begins. During this period, the gas within both the test volume (10) and the reference volume (12) starts to cool down, returning to thermal equilibrium with the ambient environment. This cooling causes a pressure decrease in both volumes. Because the test volume (10) and reference volume (12) are typically designed to be similar in size and material, the adiabatic pressure decay should be substantially similar in both. The differential pressure sensor (16) measures any deviation from this expected similarity. Crucially, the system controller (22) applies an adiabatic settling compensation model. This model, based on the ideal gas law and heat transfer principles, predicts the expected differential pressure change due to thermal settling over time. The model utilizes the initial fill pressure from sensor (26), the ambient temperature from sensor (28), and the known volumes and material properties. The differential pressure reading from sensor (16) is then continuously adjusted by subtracting the predicted thermal transient component. This compensation allows the measurement of actual leak-induced pressure decay to commence much earlier, significantly reducing the traditional "wait" time for thermal equilibrium. The duration of this phase can be reduced to 5 to 10 seconds due to compensation, compared to 30 to 60 seconds or more without it.

[0010] **Test Cycle - Measurement Phase:** Following the compensated stabilization phase, the measurement phase commences. During this period, the system controller (22) continuously records the compensated differential pressure reading from sensor (16) over a defined measurement interval, typically 5 to 30 seconds. A leak in the test volume (10) will cause its pressure to drop faster than that of the sealed reference volume (12), resulting in a measurable negative differential pressure change over time. The system controller (22) calculates the leak rate based on the rate of change of this compensated differential pressure, accounting for the test volume (10) and gas properties.

[0011] **Decision and Vent Phase:** At the end of the measurement phase, the calculated leak rate is compared against the pre-set pass/fail threshold. If the leak rate is below the maximum allowable limit, the component passes. If it exceeds the limit, the component fails. Based on this decision, an output signal is generated. Subsequently, the system controller (22) commands the vent valve manifold (20) to open, rapidly exhausting the gas from both the test volume (10) and the reference volume (12) to atmosphere, preparing the system for the next test cycle.

[0012] **Fault or Interruption:** In the event of a fault, such as a sensor failure, an inability to reach target fill pressure, or an unexpectedly large pressure deviation, the system controller (22) immediately aborts the test, vents the system, and signals an error condition. This ensures safety and prevents inaccurate test results.

6. Example Embodiments

[0013] **Embodiment 1:** A system configured for testing small, rigid components such as automotive valves or medical device housings, with an internal volume of approximately 25 ml. The reference volume (12) is 30 ml. The fill pressure is 0.3 MPa. The adiabatic settling compensation model is implemented as a first-order exponential decay function, whose parameters are determined by the internal surface area to volume ratio of the test and reference volumes, the thermal conductivity of the gas, and the wall material properties. The model is continuously updated using the absolute pressure sensor (26) and ambient temperature sensor (28) readings. The stabilization time is 8 seconds, and the measurement time is 15 seconds.

[0014] **Embodiment 2:** An arrangement adapted for testing larger, semi-rigid components like plastic containers or fuel tanks, where the test volume (10) can vary significantly (e.g., 0.5 L to 2 L) and may exhibit some deformation under pressure. The reference volume (12) is 2 L, designed to be slightly larger than the maximum expected test volume (10). The system controller (22) incorporates a pressure deformation model for the test volume (10), which uses the absolute pressure reading to predict volumetric changes during pressurization. This predicted volumetric change is factored into the adiabatic settling compensation model and the leak rate calculation to maintain accuracy despite component deformation. The fill pressure is limited to 0.05 MPa to reduce deformation.

[0015] **Embodiment 3:** A system designed for high-throughput testing where cycle time is paramount. The adiabatic settling compensation model is simplified to a fixed look-up table or a pre-calculated curve based on nominal operating conditions, rather than real-time parameter adjustment. The stabilization time is further reduced to 3 seconds. To ensure accuracy with the reduced stabilization time and simplified compensation, a robust "zero" phase is introduced after venting, where the differential pressure sensor (16) is recalibrated to zero under atmospheric pressure before each test, accounting for any sensor drift. The system includes an automated connection mechanism for rapid part loading and unloading.

7. Alternative Configurations

[0016] The described system can be configured in several alternative ways. Instead of a single differential pressure sensor (16) measuring between the test volume (10) and reference volume (12), two independent absolute pressure sensors could be employed, one in each volume, with the system controller (22) calculating the difference. While potentially adding complexity to sensor calibration, this allows for independent monitoring of each volume's pressure decay. The gas used for testing is typically dry air, but it could be an inert gas such as nitrogen or helium, particularly if the component's internal environment requires it or if higher sensitivity for very small leaks is desired when coupled with a specific leak detection method. The calibrated leak (24) can be permanently plumbed into the system with isolation valves, allowing for automated verification cycles at operator-defined intervals, rather than requiring manual connection. Furthermore, multiple calibrated leaks with different leak rates could be incorporated to verify system performance across a range of leak magnitudes. The reference volume (12) could be actively temperature-controlled to maintain it at a constant temperature, minimizing its own thermal transients and simplifying the compensation model, though this adds complexity and energy consumption.

8. Parameter Variations

Parameter	Range	Effect of Moving Towards Lower End	Effect of Moving Towards Upper End
Fill Pressure	0.05 MPa to 1.0 MPa (0.5 to 10 bar)	Reduced stress on component, lower sensitivity to small leaks.	Increased stress on component, higher sensitivity to small leaks.
Test Volume (10) Size	10 mL to 5 L	Faster thermal settling, lower resolution for given leak rate.	Slower thermal settling, higher resolution for given leak rate.
Stabilization Time	3 seconds to 30 seconds	Faster cycle time, increased reliance on compensation accuracy.	Slower cycle time, reduced reliance on compensation accuracy.
Measurement Time	5 seconds to 60 seconds	Faster cycle time, lower resolution for leak rate calculation.	Slower cycle time, higher resolution for leak rate calculation.
Differential Sensor (16) Range	±100 Pa to ±10 kPa	Higher sensitivity to very small leaks, more susceptible to noise.	Lower sensitivity to small leaks, more robust against transients.
Reference Volume (12) / Test Volume (10) Ratio	0.8 to 1.2	Greater impact of volume mismatch, potential for thermal imbalance.	Reduced impact of volume mismatch, more stable differential.

9. Additional Implementations

[0018] The adiabatic settling compensation model can be enhanced by incorporating a dynamic learning algorithm. This algorithm could continuously monitor the thermal decay characteristics of passing components and iteratively refine the model parameters for the specific test station and ambient conditions, improving the accuracy of the compensation over time. The system can be integrated into a larger manufacturing execution system (MES) or quality control system. This integration allows for automated data logging of test results, statistical process control (SPC) analysis of leak rates, and traceability of tested components. Furthermore, remote monitoring and control capabilities can be added, allowing operators to oversee multiple test stations from a central location. For components with particularly complex internal geometries or multiple internal volumes, the system could incorporate multiple pressure ports and differential pressure sensors. This allows for segmentation of the component into sub-volumes, enabling localized leak detection rather than only an overall leak rate. This would require a more sophisticated valve manifold and system controller (22) capable of managing multiple pressure zones. To further reduce measurement uncertainty, the system could employ active temperature control of the entire test fixture, including the test volume (10) and reference volume (12), maintaining them at a constant, precise temperature. This would virtually eliminate adiabatic effects and thermal gradients, simplifying the compensation model to negligible levels, though it adds significant hardware and energy consumption.

10. Figures

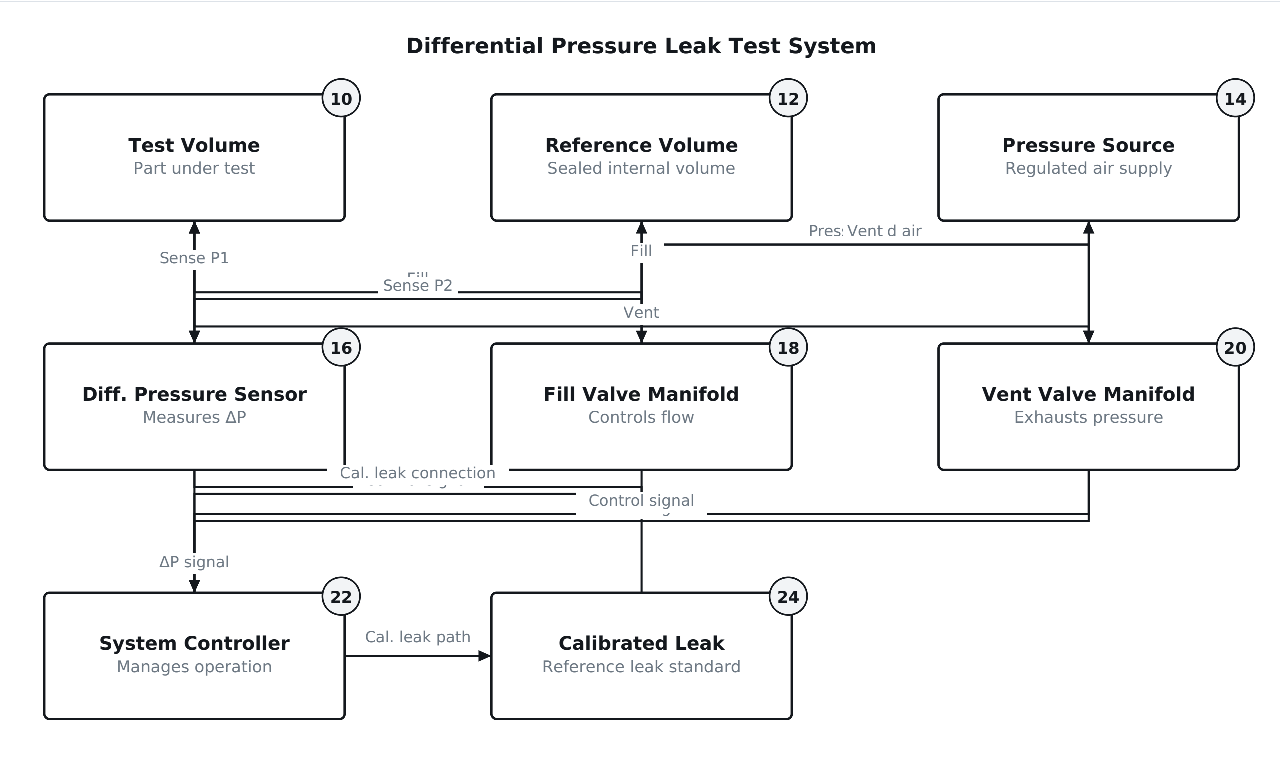

FIG. 1 A block diagram illustrating the main components and connections of the differential pressure leak testing system. PNG

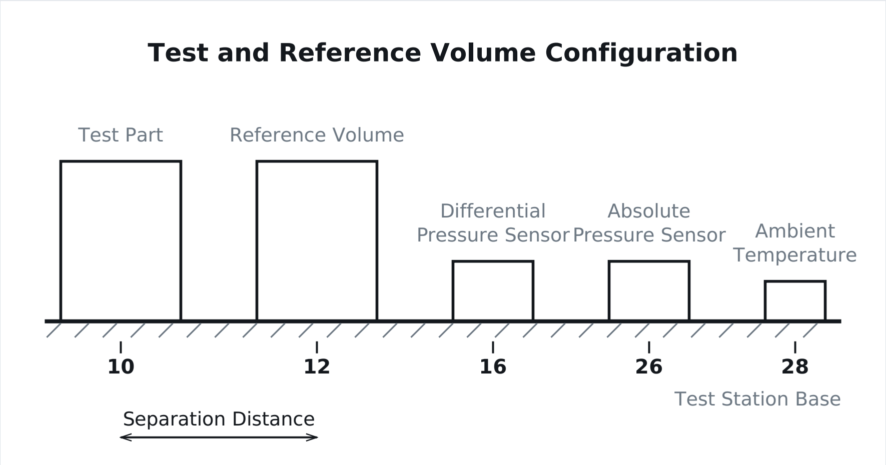

FIG. 2 An elevation view detailing the interconnections between the test volume, reference volume, and pressure sensors. PNG

OpenTechnical Publication OT-2026-000000055. Published September 15, 2026 at 11:54:45 UTC. https://opentechnical.org/p/OT-2026-000000055