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Pressurized Acid Absorption Testing of AGM Separators in VRLA Batteries: Development and Validation

Lin Liang

Jiangxi Jinma Advanced Separator Technology Co., Ltd., Ganzhou 341001, Jiangxi Province, P.R. China

***Abstract* - Absorbent glass mat (AGM) separators in valve-regulated lead-acid (VRLA) batteries operate under sustained compression within assembled plate groups. Their electrolyte supply, gas transport, and mechanical resilience are strongly influenced by separator structure and compression state. However, conventional acid absorption tests are typically performed under unconfined or poorly controlled conditions and thus fail to reproduce the pressure environment experienced in service. This study presents the design and experimental validation of a novel pressurized acid absorption testing apparatus for quantifying AGM electrolyte uptake under simulated assembly conditions. The system integrates pneumatic pressure control (0–138 kPa) with real-time liquid-level monitoring via a calibrated observation window, enabling direct and accurate measurement of acid uptake under defined compression. Validation experiments using commercial AGM separators demonstrated good repeatability across the investigated pressure range and revealed a clear decrease in acid uptake with increasing pressure, consistent with the pressure-dependent changes in AGM pore structure. Compared with conventional static immersion testing, the proposed method provides a more realistic laboratory assessment of AGM absorption behavior under compressed conditions. The apparatus offers a practical platform for separator characterization, quality control, and future investigations into the relationship between uptake behavior and VRLA battery performance.**

Keywords: Absorbent Glass Mat (AGM) separator, pressurized acid absorption, acid uptake test, VRLA battery, electrolyte immobilization, testing device, liquid level measurement, pneumatic pressurization, battery separator characterization.

I. INTRODUCTION

Absorbent glass mat (AGM) separators are a key component of valve-regulated lead-acid (VRLA) batteries because their highly porous microglass-fiber network can immobilize dilute sulfuric acid through capillary action while maintaining gas transport pathways and structural integrity [2, 7, 8, 22]. In practical VRLA cells, AGM separators not only prevent electrical contact between positive and negative plates, but also regulate electrolyte distribution, support ionic conduction, facilitate oxygen recombination during charging, and withstand sustained compression within the assembled plate group [3, 6, 9, 10].

Because electrolyte uptake under compression directly affects separator saturation, ionic transport, and battery durability, the characterization of AGM acid absorption should reflect the mechanical constraints encountered during battery assembly and operation [3, 5, 6, 10]. However, conventional test methods, such as static immersion and basic wicking tests, are generally conducted without well-defined compression and therefore cannot adequately represent the pressure-dependent absorption behavior of AGM separators in service [4, 5]. In addition, these methods usually provide only endpoint measurements and lack real-time monitoring of liquid-level change under controlled pressure conditions.

Previous studies and prior art have recognized the importance of pressure in evaluating AGM separator behavior. In particular, Chinese patent CN105628546A reported a pressure-assisted method for testing AGM separator performance [13]. Nevertheless, a laboratory-scale method that combines controlled pressurization, direct real-time liquid-level measurement, and quantitative validation of acid uptake under simulated assembly conditions remains insufficiently developed. Therefore, the key research gap is not simply the application of pressure itself, but the lack of a validated measurement approach that can quantify AGM acid absorption under defined compression states.

To address this gap, the present study reports a pressurized acid absorption testing apparatus developed from the granted Chinese Utility Model Patent CN218917142U [1], with the emphasis placed on methodological validation rather than patent description alone. Specifically, this work aims to (i) establish a controllable test configuration for AGM acid uptake under pressures of 0–138 kPa, (ii) enable direct and real-time observation of liquid-level change during absorption, and (iii) evaluate the repeatability and application potential of the method for AGM separator characterization under simulated VRLA assembly conditions.

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II. LITERATURE REVIEW

Absorbent glass mat (AGM) separators are typically fabricated from high-purity microglass fibers and formed into highly porous non-woven mats, in which fiber diameter, porosity, and pore architecture collectively govern electrolyte uptake, gas transport, and mechanical response in valve-regulated lead-acid (VRLA) batteries [2, 7, 11, 12, 22]. In practical VRLA operation, the separator must not only prevent electrical contact between positive and negative plates, but also maintain an appropriate balance between acid saturation and gas permeability, thereby supporting ionic conduction, oxygen recombination, and structural stability during service [2, 8, 22].

Under assembled plate-group conditions, AGM separators are subjected to sustained compression, and their structure responds through fiber rearrangement, slippage, and partial pore collapse [3, 5]. Previous studies have shown that compression can alter porosity, pore-size distribution, and electrolyte accessibility, which in turn influences acid uptake, saturation level, and transport behavior [3, 5, 6, 11]. Therefore, evaluating AGM absorption behavior without controlled compression provides only a partial description of separator performance under practical battery conditions.

Existing standards and industrial test methods provide useful but incomplete characterization tools. The Battery Council International (BCI) Technical Manual BCIS-03A includes recommended procedures for compression/recovery behavior, thickness under specified loads, wicking, porosity, acid weight loss, and related separator properties [4]. Other commonly used approaches, such as static immersion, vertical wicking, and gravimetric electrolyte-retention measurements, are useful for routine quality control and material screening [4, 13]. However, these methods generally do not combine controlled pressurization with direct, real-time monitoring of acid uptake during testing.

Closest prior art in the Chinese literature has already recognized the need to evaluate AGM separator behavior under pressure. In particular, Chinese patent CN105628546A describes a pressure-assisted test method using a tensile machine to obtain pressure-related parameters and acid uptake data for AGM separators [13]. Nevertheless, a laboratory-scale method that integrates sealed-vessel pressurization, direct liquid-level observation, and quantitative validation of uptake under defined compression states remains insufficiently developed. Accordingly, the main methodological gap lies not simply in applying pressure, but in establishing a validated measurement approach for quantifying AGM acid absorption under controlled compression.

Against this background, the present study is positioned not primarily as a patent description, but as a methodological investigation of pressurized acid-uptake measurement based on the granted Chinese Utility Model Patent CN218917142U [1]. The objective is to establish and validate a controllable test configuration for quantifying AGM acid absorption under 0–138 kPa, with real-time liquid-level observation and repeatability assessment under simulated VRLA assembly conditions [1].

III. MATERIALS AND METHODS

3.1 Apparatus Design and Measurement Configuration

The pressurized acid-absorption apparatus used in this study was developed to quantify electrolyte uptake of AGM separators under controlled pressurization intended to simulate assembly-related test conditions [1]. As shown in Figure 1, the system adopts a compact vertical configuration that integrates a sealed test vessel, a pneumatic loading module, a specimen-positioning assembly, and a visual liquid-level measurement unit into a single laboratory-scale platform [1].

The apparatus mainly consists of a pressurized vessel, a movable sealing cover, a pneumatic cylinder, guide columns, a locking mechanism, an AGM sample holder, and a transparent observation window with an adjacent graduated scale [1]. During operation, the sealing cover moves vertically to close the vessel and maintain a stable sealed environment, while the sample holder fixes the AGM separator specimen at a defined position inside the chamber. This arrangement allows acid-uptake testing to be conducted under controlled pressurization while minimizing leakage and mechanical misalignment [1].

All components in contact with sulfuric acid were fabricated from corrosion-resistant materials, including 316 stainless steel, polypropylene (PP), and PTFE-lined sealing elements [1]. The observation window was made of thick borosilicate glass or another chemically resistant transparent material to permit direct monitoring of liquid-level variation during testing [1]. The overall footprint of the apparatus is approximately 400 mm × 350 mm × 550 mm, allowing installation on a standard laboratory bench [1].

For quantitative readout, a graduated scale with 1 mm resolution was aligned with the observation window, and the uptake volume was determined from the measured liquid-level drop together with the known internal cross-sectional area of the vessel [1]. The pneumatic module provides pressure control over the range of 0–138 kPa, thereby enabling laboratory evaluation of AGM absorption behavior under defined pressurization conditions relevant to VRLA separator testing [1,4,13].

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Compared with conventional static immersion or simple wicking tests, the present apparatus combines sealed-vessel pressurization with direct visual liquid-level measurement in a single test configuration [4,13]. Accordingly, the apparatus is presented here not merely as a mechanical device description, but as a test platform for methodological validation and separator characterization under simulated VRLA assembly conditions [1].

3.2 Figures, Tables and Schemes

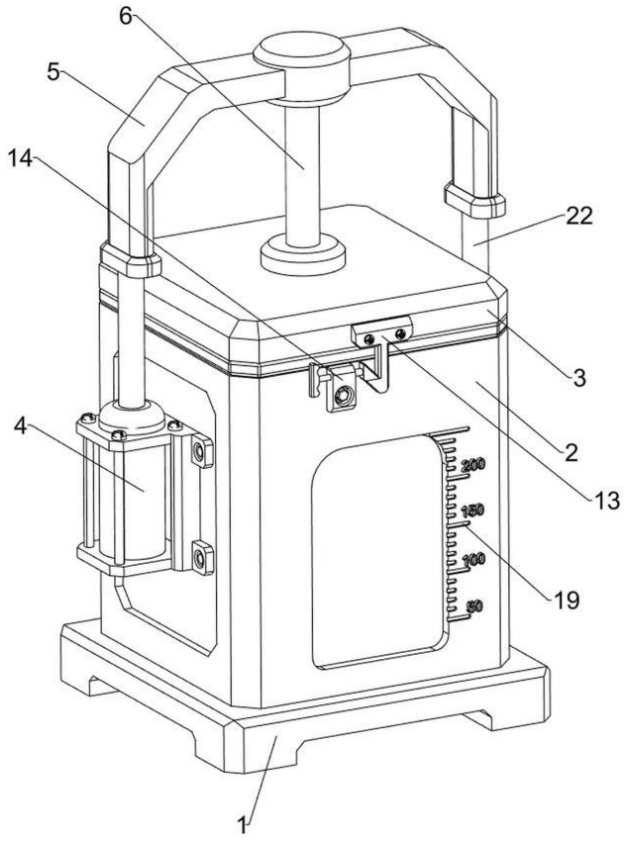

Figure 1: Schematic representation of the pressurized acid-absorption apparatus

3.3 Working Principle

The measurement principle of the present apparatus is based on controlled pressurization of the AGM specimen combined with direct volumetric quantification of electrolyte uptake through liquid-level variation [1]. A sealed vessel is subjected to a defined gas pressure using a pneumatic loading system, thereby imposing a controlled compressive state on the AGM separator during testing. This pressurization is intended to reproduce assembly-related mechanical conditions relevant to VRLA battery plate groups [3,5].

Under the applied pressure, the AGM separator absorbs sulfuric acid from the reservoir through capillary-driven transport. As absorption proceeds, the liquid level inside the vessel decreases.

Table 1: Essential components of the pressurized acid-absorption apparatus used in this study

No.	Component	Function in this study	Material used	Key specification
1	Support base/frame	Provides structural stability for the apparatus	Carbon steel with corrosion-	400 mm × 350 mm × 80 mm
2	Pressurized vessel	Contains sulfuric acid and the AGM specimen	316 stainless steel with acid-	Internal volume ≈ 2.5 L
3	Movable sealing cover	Seals the vessel during pressurized	316 stainless steel with	Quick-locking structure
4	Pneumatic cylinder	Applies controllable vertical motion	Aluminum alloy body;	Stroke 150 mm; working pressure
5	Guide columns	Maintain vertical alignment of	316 stainless steel	Diameter 20–25 mm
6	AGM sample holder	Fixes the separator specimen at a	PP or PTFE	Adjustable to specimen size
7	Observation window	Allows direct monitoring of liquid-level change	Borosilicate glass or acid-resistant	180 mm × 120 mm
8	Graduated scale	Enables reading of liquid-level	Engraved glass or stainless	0–200 mm; 1 mm resolution
9	Locking mechanism	Ensures airtight closure during testing	Stainless steel	With safety interlock

This change is monitored in real time through a transparent observation window and a calibrated graduated scale, allowing direct measurement of the absorbed volume [1].

The absorbed acid volume is determined by:

$$V_{absorbed} = A \times (h_{initial} - h_{final})$$

Where

$V_{absorbed}$ is the absorbed electrolyte volume (cm^3),
A is the internal cross-sectional area of the vessel (cm^2), and
$h_{initial}$ and h_{final} are the initial and final liquid levels (cm), respectively.

The absorbed mass can be obtained by multiplying the volume by the electrolyte density. The results can be further normalized by specimen area or mass to yield absorption capacity (e.g., g/cm^2 or saturation percentage). This approach enables quantitative evaluation of pressure-dependent

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absorption behavior, which is not accessible using conventional ambient-pressure methods [4,5,13].

3.4 Experimental Procedure

All experiments were conducted following a standardized procedure to ensure repeatability and comparability of results.

3.4.1 Sample preparation

AGM separator specimens were cut to predefined dimensions and placed on the sample holder inside the pressurized vessel. The initial mass, thickness, and geometric dimensions were recorded prior to testing [1].

3.4.2 System sealing and electrolyte introduction

The vessel was hermetically sealed using the movable cover and locking mechanism. A known volume of sulfuric acid electrolyte (typically 1.28 g/cm³, 38 wt%) was introduced until the liquid level reached a predefined reference position on the graduated scale [1].

3.4.3 Pressure application

The internal gas pressure was adjusted to the target value (e.g., 20–138 kPa) using the pneumatic control system and maintained constant throughout the test [1,3].

3.4.4 Liquid-level monitoring

The liquid level was recorded at specified time intervals until stabilization was observed. Simultaneously, pressure was monitored to ensure stable test conditions [1].

3.4.5 Data processing

The absorbed volume was calculated using Equation (1), and converted to mass using electrolyte density. Results were normalized to obtain absorption capacity. Multiple replicates were performed to ensure statistical reliability [1].

3.5 Safety Considerations

The apparatus incorporates standard safety features, including a pressure relief valve, over-pressure protection, and a mechanical locking system to prevent accidental opening under pressurized conditions [1].

All experiments were conducted using appropriate personal protective equipment (acid-resistant gloves, safety goggles, and lab coats) and within a ventilated environment. After testing, the vessel was neutralized and cleaned prior to disassembly.

The described configuration provides a controlled and reproducible framework for evaluating pressure-dependent electrolyte uptake in AGM separators, supporting both material characterization and methodological validation [1,4].

IV. RESULT

4.1 Test Conditions

To evaluate the applicability and repeatability of the proposed pressurized acid-absorption apparatus, validation experiments were conducted using commercial AGM separator specimens with a thickness of 1.6 mm and a porosity of 92–94%. The purpose of these experiments was to examine whether the apparatus could resolve pressure-dependent changes in electrolyte uptake under defined laboratory pressurization conditions relevant to VRLA separator evaluation [3,5,6].

All tests were carried out using sulfuric acid electrolyte with a density of 1.28 g cm^{-3} (38 wt%), which is representative of standard VRLA battery electrolyte. The laboratory temperature was maintained at 25 ± 1 °C. The applied pressure levels were 0, 20, 50, 100, and 138 kPa, covering the range typically considered relevant to AGM separator compression in assembled plate groups [3,5]. The specimen size was 100 mm × 100 mm, and each pressure level was tested using five independent specimens. The test endpoint was defined as stabilization of the liquid level, which was typically reached within 30–60 min.

4.2 Pressure-Dependent Acid Uptake

Table 2: Acid uptake of AGM separator under different applied pressures (n = 5)

Applied pressure (kPa)	Acid uptake (g cm^-2, mean ± SD)	RSD (%)	Saturation level (%)	Relative change vs 0 kPa (%)
0	0.812 ± 0.018	2.22	68.4	0
20	0.785 ± 0.012	1.53	66.1	-3.3
50	0.743 ± 0.009	1.21	62.5	-8.5
100	0.681 ± 0.011	1.62	57.3	-16.1
138	0.629 ± 0.014	2.23	53	-22.5

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As shown in Table 2, acid uptake decreased monotonically with increasing applied pressure. The average uptake declined from 0.812 g cm^-2 at 0 kPa to 0.629 g cm^-2 at 138 kPa, corresponding to a reduction of 22.5%. This trend is consistent with previous reports that compression can reduce accessible pore volume and alter the pore structure and liquid-storage behavior of AGM separators [3,5,6,11]. The results therefore indicate that the present apparatus is capable of capturing the pressure dependence of AGM acid absorption over the investigated range.

4.3 Repeatability Analysis

The relative standard deviation ranged from 1.21% to 2.23% across the tested pressure levels, with an average value of 1.76%. These results indicate good repeatability for laboratory evaluation of AGM separator acid uptake. In particular, the relatively narrow dispersion of the measurements suggests that the combination of sealed-vessel testing, controlled pressurization, and direct liquid-level readout can provide stable uptake measurements under defined test conditions.

4.4 Comparison with Conventional Methods

A comparison experiment was performed on the same AGM batch using a conventional static immersion method without pressure control. At 50 kPa, the uptake value measured by the pressurized apparatus was 18.7% lower than that obtained by the static method. This result suggests that ambient-pressure measurements may overestimate electrolyte uptake when the separator is intended to operate under compressed conditions [4,13]. From a methodological perspective, the pressurized test therefore provides a more application-relevant assessment of AGM absorption behavior than unconstrained static immersion alone.

4.5 Measurement Uncertainty and Practical Implications

The main sources of uncertainty in the present measurements include liquid-level reading error, temperature-dependent variation in electrolyte density, and pressure fluctuation during testing. In this study, the liquid-level reading error was estimated to be ±0.5 mm, the effect of temperature fluctuation on acid density was estimated to be ±0.3%, and the pressure stability was within ±2% of the set value. Based on these contributions, the combined expanded uncertainty of the acid-uptake measurement was estimated to be ±3.8% (k = 2).

Taken together, the validation results show that the proposed apparatus can provide repeatable measurements of AGM acid uptake under controlled pressurization and can distinguish the change in uptake behavior across a practically relevant pressure range. The method is therefore suitable for separator characterization, comparative material screening, and further methodological studies. However, the relationship between the measured uptake values and full battery performance should be established in future work through direct correlation with cell-level assembly and electrochemical data [2,22].

V. DISCUSSION

The present apparatus provides several methodological advantages for evaluating acid uptake of AGM separators under controlled pressurization.

First, it combines pressure application and direct liquid-level measurement within a sealed test configuration, allowing electrolyte uptake to be quantified under defined laboratory pressurization conditions relevant to VRLA separator evaluation.

Compared with conventional static immersion or basic wicking tests, this configuration enables assessment of pressure-dependent absorption behavior that is difficult to capture using ambient-pressure methods alone.

Second, the transparent observation window and graduated scale allow direct visual monitoring of liquid-level variation during testing. This arrangement supports time-resolved observation of uptake behavior and simplifies volumetric readout compared with endpoint-only measurements. As a result, the method can provide a more direct laboratory assessment of acid-uptake change during pressurized testing.

Third, the apparatus adopts a compact and modular structure suitable for routine laboratory operation. The sealed vessel, locking mechanism, and pneumatic control system allow the test environment to be maintained in a stable and controlled manner during measurement. This configuration is therefore suitable for comparative separator characterization and method development under defined test conditions.

Based on the validation results obtained in this study, the method showed good repeatability across the investigated pressure range and captured a monotonic decrease in acid uptake with increasing pressure. In comparison with the conventional static immersion method, the pressurized test yielded lower uptake values under compressed conditions, suggesting that it may provide a more application-relevant assessment of AGM separator behavior in assembled plate-group environments.

It should be noted, however, that the present results represent validation of a measurement method rather than

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direct evidence of improved battery-level performance. The relationship between pressurized uptake behavior and battery-level properties (e.g., oxygen recombination, charge acceptance, cycle life, safety) should be established in future cell-level studies.

Overall, the combination of controlled pressurization, sealed-vessel testing, and direct liquid-level measurement provides a useful platform for AGM separator characterization, comparative material screening, and further methodological studies.

VI. CONCLUSION AND FUTURE

This study presents a pressurized acid absorption testing apparatus for AGM separators and provides its preliminary experimental validation under defined laboratory conditions relevant to VRLA battery assembly. By integrating pneumatic pressure control, sealed-vessel testing, and real-time visual liquid-level monitoring, the apparatus enables quantitative evaluation of acid uptake over a pressure range of 0–138 kPa.

The validation results showed good repeatability across the investigated conditions, with an average relative standard deviation of approximately 1.8%, and demonstrated a clear decrease in acid uptake with increasing pressure.

Compared with conventional static immersion testing, the pressurized method yielded lower uptake values under compressed conditions, indicating that pressure-controlled testing may provide a more application-relevant laboratory assessment of AGM separator absorption behavior than ambient-pressure methods alone.

The present results therefore support the use of the apparatus as a practical platform for AGM separator characterization, comparative material screening, and further methodological studies under simulated VRLA assembly conditions.

Future work will focus on improving both the apparatus and the validation methodology. Planned developments include integration of digital pressure sensing, higher-resolution liquid-level detection, and automated data acquisition and analysis. Additional studies will include multi-sample testing, temperature-controlled experiments, pressure-cycling protocols, and validation across AGM separators with different fiber structures, porosities, and thicknesses. A particularly important next step is to calibrate the relationship between the applied apparatus pressure and the effective compressive state of the specimen, and to correlate the measured uptake behavior with battery assembly characteristics and electrochemical performance.

In summary, the proposed apparatus provides a controlled and repeatable framework for investigating AGM acid uptake under pressurized conditions and may support more realistic laboratory evaluation of separator behavior relevant to VRLA battery applications.

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AUTHOR'S BIOGRAPHY

Lin Liang is a Technical Director specializing in absorbent glass mat (AGM) separator technology and lead-acid battery materials at Jiangxi Jinma Advanced Separator Technology Co., Ltd., China. He has extensive experience in AGM separator manufacturing, process optimization, and battery material engineering. His work focuses on separator structure design, electrolyte absorption performance, and industrial-scale production systems for VRLA batteries. Mr. Liang is a co-inventor of multiple utility model patents related to AGM separator manufacturing and testing equipment and has published research in the field of battery materials and separator technology. He is also a member of The American Ceramic Society.

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