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Article

A Study on the Effects of Airflow and Static Electricity on Analytical Balance Weighing

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Abstract: This study investigates the influence of environmental factors — specifically airflow and electrostatic charge — on the accuracy of analytical balance measurements. A series of controlled experiments were conducted to evaluate mass deviations under varying ventilation speeds and electrostatic charge intensities. High-precision analytical balances from METTLER TOLEDO, Sartorius, and Ohaus were employed, together with instruments such as ionizing blowers and anemometers. Results indicate that even minor airflow disturbances (≥0.2 m/s) and low-level electrostatic charges (≥1 kV) can induce statistically significant weighing errors ($p < 0.01$), with airflow causing more immediate and pronounced deviations, reaching up to ±0.4 mg. Practical control strategies — including environmental isolation, static neutralization, and optimized weighing protocols — are proposed. The study presents a comprehensive comparison of interference sources and underscores the importance of environmental control in high-precision weighing. Future work will extend the tests to a broader range of balance models and assess performance under more extreme operational conditions.

Keywords: analytical balance; airflow interference; electrostatic disturbance; weighing error; mass measurement accuracy

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1. Introduction

1.1. Background and Significance

Analytical balances play a crucial role in analytical chemistry. The precision of weighing results directly affects the accuracy and reliability of experimental outcomes. As a fundamental instrument in laboratories, even minor deviations in measurement can lead to significant errors in subsequent analysis, especially in trace analysis and quantitative experiments.

1.2. Problem Statement

In real-world laboratory settings, measurement errors caused by airflow and electrostatic charges are frequently observed. These environmental disturbances can lead to fluctuations in weighing data, compromising result reliability and hindering repeatability. Although such effects may seem subtle, they can accumulate and produce substantial errors, particularly when weighing micro-or ultra-micro samples.

1.3. Research Objectives and Content Overview

This study aims to systematically evaluate the effects of airflow and electrostatic interference on analytical balance measurements and to propose effective control strategies. By identifying the major sources of environmental interference and developing mitigation approaches, the research seeks to improve the accuracy and reliability of weighing results in high-precision applications [1].

2. Literature Review

2.1. Research Progress on the Effects of Airflow on Precision Weighing

The influence of airflow on analytical balance performance has received growing attention in both academic and industrial laboratories. Air disturbances, even those imperceptible to humans, can significantly impact precision weighing by generating micro-level mechanical forces that disturb the weighing pan or load cell.

Internationally, scholars have conducted experimental studies under various airflow conditions, often simulating different laboratory scenarios, such as weighing in fume hoods or near ventilation systems. These studies confirm that even a low-speed airflow of less than 0.3 m/s can result in significant deviations when using microbalances with readability at or below 0.1 mg. Moreover, factors like room air conditioning, operator movement, and the opening of balance doors are all identified as variables that affect repeatability and measurement stability.

In terms of theoretical analysis, researchers have constructed airflow field models using Computational Fluid Dynamics (CFD). These models allow for the visualization of airflow distribution and turbulence intensity around the weighing area, particularly within draft shields. Simulations suggest that air vortices formed during balance door operations or inside poorly designed enclosures can cause microfluctuations lasting several seconds, enough to affect precision measurements.

To address this issue, control technologies have emerged. These include:

1) The development of enclosed weighing cabinets with laminar flow suppression;
2) Draft shields optimized for turbulence reduction;
3) Intelligent balance software that detects unstable weighing conditions triggered by airflow and issues corrective prompts or automatic delays.

Domestically, several studies have replicated airflow experiments in university labs using wind tunnels or enclosed chambers. However, the number of high-resolution datasets and advanced simulations remains limited. Local research primarily focuses on practical guidance for bench placement, room ventilation standards, and training for operators to minimize movement-induced airflow during weighing.

Overall, international research has advanced both empirical and modeling approaches, while domestic studies emphasize application in standard laboratory settings [2,3].

2.2. Research Progress on the Effects of Static Electricity on Precision Weighing

Static electricity is a widely acknowledged yet often underestimated factor that contributes to mass measurement error. Its influence becomes particularly pronounced when dealing with fine powders, plastic containers, or samples handled in dry environments. Electrostatic forces act between the charged sample/container and the grounded weighing system, either attracting or repelling the load, leading to unstable or incorrect readings.

From the global research perspective, extensive theoretical work has been carried out to model the mechanism of electrostatic interference. Charge accumulation due to triboelectric effects, contact separation, or environmental dryness has been quantitatively described using electrostatic field equations. Several studies have modeled the electrostatic force exerted by static fields on weighing pans as a function of charge density and material dielectric properties.

Detection methods such as electrostatic field meters, Faraday cages, and non-contact voltmeters have been employed in laboratory experiments to measure the presence and strength of electrostatic charges around the balance. Such methods reveal that even a few kilovolts of surface charge potential can induce errors exceeding several milligrams on high-precision balances.

To mitigate these effects, researchers have tested a range of countermeasures:

1) The application of ionizing blowers to neutralize charges.
2) Selection of conductive or anti-static containers.
3) Maintaining relative humidity above 45% in weighing environments.
4) Implementation of anti-static coatings inside balance enclosures.

In domestic studies, a number of papers have focused on evaluating static interference by weighing the same sample across containers of different materials and shapes. These studies often show large deviations in weight depending on whether the material was glass, plastic, or metal. Some local labs have implemented low-cost ionizing fans and compared performance before and after static discharge to support the feasibility of using such devices in teaching or industrial settings.

While international studies delve deeper into theoretical modeling and material-specific behaviors, domestic research highlights practical error ranges and cost-effective solutions suitable for daily laboratory work [4].

2.3. Error Control Methods and Trends (with Reference to METTLER TOLEDO, Sartorius, and Ohaus)

To address the challenges posed by airflow and electrostatic interference, major analytical balance manufacturers have introduced a range of technologies and practices aimed at minimizing environmental influences. These methods include physical shielding, electrostatic neutralization, and smart calibration systems [5].

2.3.1. Draft Shields and Enclosed Chambers

Draft shields are among the most commonly used physical barriers to reduce the impact of air turbulence. Modern balances often come equipped with multi-panel, quick-lock draft shields that allow for easy sample access while maintaining airflow isolation. Some models, especially in the microbalance category, feature fully enclosed glass chambers with minimal internal air volume to suppress turbulence.

Manufacturers like METTLER TOLEDO have developed balance-specific enclosures with Fast Draft Shield (FDS) mechanisms and climate-controlled weighing cabinets, which help isolate weighing areas from temperature and pressure changes. Sartorius' Cubis® II system offers customizable draft shield modules, which can be integrated with sensors that detect door openings and trigger automatic data hold functions to avoid misreading due to movement-induced air currents.

2.3.2. Electrostatic Control Technologies

Static charge is typically controlled using ionizing equipment, including ionizing blowers, ionizing bars, and built-in anti-static modules. For instance, some high-end models from METTLER TOLEDO XPR series integrate anti-static kits that neutralize charges on samples or containers during weighing. These devices emit a stream of positive and negative ions to balance the surface potential of materials.

Sartorius offers external ionizing bars and anti-static sample holders, while Ohaus includes anti-static coating on windshields and weighing pans in their Explorer® series. In addition, the use of grounded weighing vessels and conductive tongs are standard recommendations across all brands.

2.3.3. Smart Calibration and Compensation Features

Modern analytical balances often include automatic internal calibration functions, such as METTLER TOLEDO's FACT (Fully Automatic Calibration Technology) and Sartorius' isoCAL feature. These systems automatically recalibrate the balance in response to time, temperature, or other environmental triggers, maintaining consistent accuracy without manual intervention.

Some balances now incorporate real-time environmental monitoring sensors, which measure air pressure, temperature, and humidity. The measured values can be used to generate error correction models or trigger operator alerts if the environment exceeds acceptable limits. Building upon these specific technologies, current developments in analytical balance design increasingly emphasize automation, integration, and environmental adaptability.

2.3.4. Application Trends

From a broader perspective, the trend in error control technology is toward:

1) Automation: Reducing operator-induced disturbances through robotic sample placement and auto-door operation;
2) Integration: Combining weighing modules with environmental sensors and software-driven feedback systems;
3) Miniaturization: Designing compact enclosures with precise airflow control for ultra-micro weighing;
4) Digital documentation: Using balance software (e.g., EasyDirect™, LabX®, QApp™) for automatic logging, error tracking, and statistical analysis.

These measures represent a shift from passive protection (e.g., shields) to active environmental interaction, in which the balance dynamically responds to real-time interferences and corrects for them accordingly.

2.4. Research Status at Home and Abroad

2.4.1. Research Progress on the Effects of Airflow on Precision Weighing

Airflow is one of the most prominent environmental factors causing weighing instability in high-precision analytical balances. Internationally, manufacturers and laboratories have conducted systematic studies to quantify this impact.

METTLER TOLEDO emphasized that even minor air movements — caused by nearby air conditioning, open doors, or fume hoods — can result in significant weighing variability, especially in balances with readability of 0.1 mg or less. Technical director Ian Ciesniewski identified airflow as the leading source of repeatability deterioration in balance performance.

Flow Sciences investigated weighing errors in ventilated enclosures and identified unbalanced exhaust fans and structural vibrations as major contributors to measurement instability. Their study recommends placing balances on anti-vibration stone-top tables, ensuring balanced ventilation, and avoiding high-turbulence zones.

A white paper from Erlab (a global manufacturer specializing in laboratory ventilation and safety equipment) detailed airflow management during precision weighing in ductless fume hoods. It specifies airflow velocities between 0.4 and 0.6 m/s as optimal for safety and performance. Their filtration workstations include structural dampers and anti-vibration isolation to reduce environmental disturbance.

Shimadzu (a leading Japanese manufacturer of precision analytical instruments) further confirmed that external airflow and internal convection currents in the balance chamber can cause fluctuations. The company recommends enclosing the weighing area and minimizing external air exposure by using sliding doors and wind-shielded enclosures.

Domestic progress: In China, researchers at Zhejiang University and Nankai University have conducted practical evaluations of airflow interference under different lab setups. Their work showed that local static zones in cleanroom environments or weighing booths significantly improve microbalance repeatability. A 2021 experiment also demonstrated that even small body movements of nearby operators can alter local airflow patterns and introduce measurable deviations in weighing readings.

2.4.2. Research Progress on the Effects of Static Electricity on Precision Weighing

Electrostatic charge is another major interference factor in analytical weighing, especially in dry, climate-controlled laboratories or when using non-conductive materials like plastic.

METTLER TOLEDO developed the StaticDetect™ function to automatically detect electrostatic interference. Their studies confirm that charged samples or containers can cause fluctuating or biased measurements. Eliminating these charges via ionizers before weighing significantly stabilizes results.

According to Fisher Scientific, frictional contact — such as drying glassware with a cloth or handling plastic vessels with gloves — can generate detectable static charges. These charges act between the sample and the weighing pan, resulting in inconsistent readings.

Darwell (a company specializing in static control solutions) lists common weighing errors due to static electricity: non-reproducible results, drifting display values, and sample dispersion. The company recommends using conductive containers, operating in humidified environments, and utilizing ionizing blowers to remove charge accumulation.

Lab Bulletin also highlights electrostatic fields as one of the "eight primary causes of instability" in analytical balances. They emphasize grounding, anti-static sample holders, and humidity regulation as essential measures. Similar to international efforts, domestic research has increasingly focused on material-specific static charge effects and practical mitigation strategies.

Domestic progress: Researchers at the China Institute of Metrology have published findings on the relationship between static buildup and material type. One study compared polyethylene (PE), polypropylene (PP), and polystyrene (PS) containers, finding PS retained charges up to 5 kV after contact. Tsinghua University's chemical engineering lab further validated that static in plastic containers caused up to 1.8 mg error in 0.1 mg resolution balances. Practical recommendations include placing samples near ionizers for 10 seconds prior to weighing and maintaining ambient humidity above 45% to reduce triboelectric effects.

3. Experimental Section

3.1. Experimental Instruments and Materials

To ensure accurate and reliable results, this study selected analytical balances from leading international manufacturers, specifically avoiding domestic and Japanese-made balances. The selected instruments include models from METTLER TOLEDO, Sartorius, and Ohaus, each equipped with high-precision features suitable for micro-weighing tasks. Additional accessories were selected for controlling airflow and simulating electrostatic interference.

3.1.1. Analytical Balances

1) METTLER TOLEDO

The METTLER TOLEDO MX204/A2 balance, shown in Figure 1, was selected for its high readability and rapid stabilization time. It is equipped with an automatic internal calibration system (FACT) and a touchscreen interface.

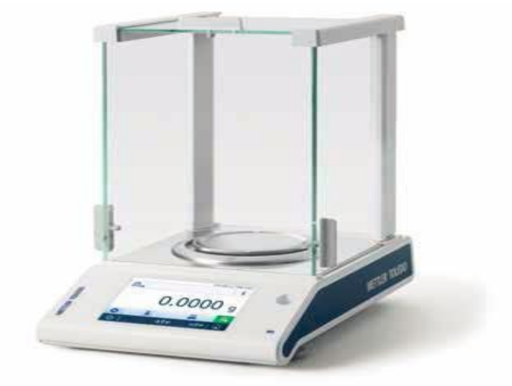

Figure 1. METTLER TOLEDO MX204/A2 Analytical Balance Used in This Study.

2) MX204/A2

Precision and Capacity: Offers a precision level of 0.001 g (1 mg), with a weighing range between 200 g and 500 g. The readability ranges from 0.002 mg to 1 mg depending on sample conditions.

Functional features: Some models are equipped with powder and liquid dosing modules, allowing upgrade to fully automated sample and solution preparation. The unit features a quick-release draft shield and suspended weighing pan, making cleaning easy. Data processing and documentation are streamlined via EasyDirect software.

3) ML Series 2

Precision and Capacity: Offers multiple configurations with varying precision and capacity, suitable for diverse laboratory requirements.

Functional features: Uses MonoBloc single-module sensor technology, providing strong resistance to shock and overload, thus ensuring stable weighing performance. The device includes a backlit LCD display and multiple built-in weighing applications such as basic weighing and statistical functions. Power options include AC and battery. Connectivity is supported via RS232 and USB, allowing data export to Excel and other programs.

4) MR204/A2

Precision and Capacity: Maximum capacity of 220 g with a readability of 0.1 mg and a typical repeatability of 0.08 mg.

Functional features: Features a 2-second stabilization time and FACT (Fully Automatic Calibration Technology) for time-and temperature-based internal calibration. Equipped with a 4.5-inch color TFT touchscreen, user management functions, and 8 built-in applications with statistical analysis capabilities. The QuickLock draft shield allows easy disassembly, while the full metal housing ensures durability (IP41 protection level). The device also supports energy-saving mode.

Sartorius

1) CPA225D

Precision and capacity: Precision up to 0.1 mg, suitable for general analytical tasks in laboratory environments.

Functional features: A classic high-accuracy model, known for stability and reliability. The balance offers a minimum four-digit decimal display, ensuring excellent resolution. It meets the needs of various precision weighing operations.

2) Practum224-1CN

The Sartorius Practum224-1CN model (Figure 2) features advanced sensor technology and user-friendly weighing modes suitable for high-precision tasks under controlled laboratory conditions.

Figure 2. Sartorius Practum224-1CN Analytical Balance with a High-Contrast Display and Modular Functionality.

Precision and capacity: A high-precision electronic analytical balance with 0.1 mg readability and approximately 220 g weighing capacity.

Functional features: Incorporates advanced sensor technology to ensure measurement reliability and precision. Features a large, easy-to-read LCD screen with a user-friendly interface. Multiple weighing modes are available, including piece counting, percent weighing, and check weighing.

3) Cubis Series

Precision and capacity: Offers a wide range of readability and capacity options, from micro to semi-macro weighing.

Functional features: Utilizes electromagnetic force compensation for high precision and fast response. The modular design enhances upgrade flexibility and maintenance ease. Multiple communication ports (e.g., RS232, USB, Ethernet) facilitate integration with PCs, printers, and other devices for data transmission and recording.

4) Ohaus

Explorer® Series

The Ohaus Explorer balance utilized in this experiment is shown in Figure 3. It includes a SmarText™ touchscreen system and an anti-static glass draft shield, making it suitable for measurements under airflow or static-prone conditions [6].

Figure 3. Ohaus Explorer Analytical Balance with Touchscreen Control and Anti-static Enclosure.

Precision and Capacity: Multiple models available with varied specifications, including SPX123 (120 g × 0.001 g), SPX2201 (2200 g × 0.1 g), and SPX2202 (2200 g × 0.01 g).

Functional features: Equipped with a 5.7-inch touchscreen and the intuitive SmarText™ 2.0 graphical interface. The anti-static coated glass draft shield and hands-free automatic doors improve operational efficiency. Modular design allows separation of weighing base and terminal. Includes fully automatic internal calibration, rapid stabilization time, four wireless sensors, and 11 language options including Chinese.

5) Scout Series

Precision and Capacity: For example, the SPX222 model provides a 220 g capacity with 0.01 g readability.

Functional Features: High-quality construction with anti-buoyancy plates under the weighing chamber ensures minimal airflow interference. Easily detachable chamber design allows for easy cleaning. Multiple weighing applications are supported, including basic, percent, check, and piece counting modes. Supports RS232, USB host/device, and Ethernet communication for convenient data export and device integration.

3.1.2. Experimental Samples

Two types of sample materials were selected for analysis:

1) Powdered materials: e.g., talc and silica powders, characterized by small particle sizes and high surface area, which make them susceptible to electrostatic accumulation and airflow disturbance.
2) Granular materials: e.g., glass beads and polymer pellets, larger in size and mass, generally less affected by environmental interferences.

3.1.3. Airflow Control Devices

To simulate controlled airflow environments and test its influence on weighing performance, the following devices were used:

1) Variable-speed fume hood: Simulates typical laboratory airflow conditions.
2) Anemometer: Measures wind velocity around the weighing zone to ensure precise control.
3) Balance draft shield: Built-in or external enclosures used to isolate the weighing chamber from airflow.

3.1.4. Electrostatic Simulation Devices

To evaluate the effects of electrostatic interference on weighing accuracy, the following equipment was employed:

1) Electrostatic generator: Applies varying levels of surface charge to samples and containers.
2) Ionizing blower: Neutralizes static charges on sample surfaces before weighing.
3) Electrostatic field meter: Measures the surface potential of charged objects for data verification and control.

3.2. Experimental Design

This study was structured to assess the individual effects of airflow and static electricity on the weighing accuracy of high-precision analytical balances. Two separate sets of experiments were designed: one focusing on airflow disturbances and the other on electrostatic interference.

3.2.1. Airflow Experiments

The airflow experiments were designed to simulate varying wind speeds under controlled laboratory conditions, with a particular focus on mimicking the environment inside a fume hood. The goal was to quantify the deviation in weighing results under different airflow intensities.

Experimental Procedure:

1) Baseline measurement: Samples were weighed under calm, wind-free conditions to establish control data.
2) Simulated airflow conditions: The airflow speed was gradually increased using a variable-speed fume hood, with measurements taken at 0.2 m/s, 0.4 m/s, and 0.6 m/s.
3) Repeat testing: Each airflow condition was repeated three times to ensure reproducibility and minimize experimental noise.
4) Fume hood airflow analysis: Air distribution patterns within the fume hood were documented using an anemometer and smoke testing, allowing for correlation between local turbulence and weighing error.

The airflow speed was gradually increased using a variable-speed fume hood, with measurements taken at 0.2 m/s, 0.4 m/s, and 0.6 m/s. Each condition was repeated three times to ensure reproducibility.

To better illustrate the experimental workflow and variable relationships, a schematic diagram of the airflow disturbance test is provided in Figure 4.

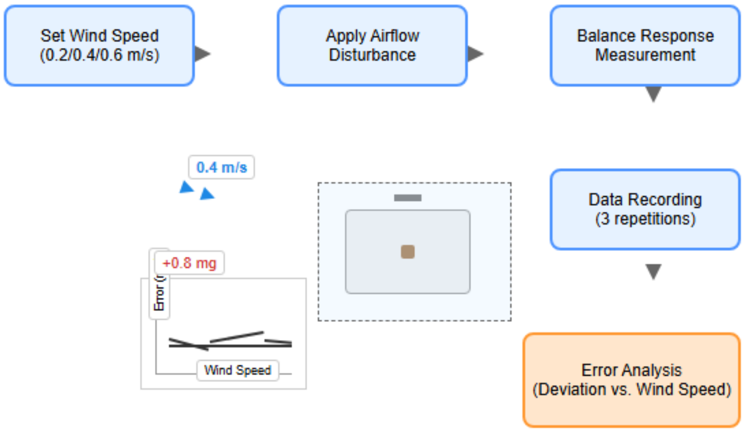

Figure 4. Airflow Disturbance Experiment.

Figure 4 Experimental design for airflow disturbance tests at varying ventilation speeds. The diagram shows the experimental workflow from wind speed setting (left) through disturbance application (center) to balance measurement and error analysis (right).

Data Analysis Goals:

1) Determine the relationship between airflow speed and weighing deviation.
2) Assess the effectiveness of draft shields in reducing airflow-induced measurement fluctuations.
3) Compare instrument response times and error ranges across different balance models under turbulent conditions.

To ensure experimental relevance, airflow settings were determined according to standard laboratory ventilation practices and equipment specifications.

3.2.2. Electrostatic Experiments

This segment aimed to evaluate how electrostatic charges of varying magnitudes influence weighing stability and accuracy. In particular, the experiment examined how sample composition and particle size affect the accumulation and dissipation of static electricity.

Experimental Procedure:

1) Sample pre-treatment: Samples of identical mass but varying particle sizes (e.g., fine powder vs. coarse granules) were selected.

2) Electrostatic charging: A static generator was used to apply surface charges of 1 kV, 3 kV, and 5 kV to containers and sample materials.
3) Measurement under charge: The charged samples were placed on the analytical balance, and weighing data were recorded over a fixed time interval.
4) Charge neutralization: Ionizing blowers were then used to remove static charges from the same samples, followed by a second set of weighings to compare measurement stability.
5) Control setup: Non-charged samples were weighed under identical environmental conditions to establish reference values.

Specific Investigations:

1) The effect of particle size on static accumulation (fine powders generally retain more charge).
2) The effectiveness of charge neutralization using ionizing equipment.
3) The behavior of different balance models in the presence of static interference (e.g., weighing drift, data instability).

Supplemental references were used to confirm the voltage levels typically encountered in laboratory environments and validate electrostatic discharge safety limits.

3.3. Data Collection Methods

A rigorous approach was adopted to ensure the reliability, reproducibility, and traceability of all collected data. Control variables were carefully managed to isolate the influence of airflow and electrostatic interference.

3.3.1. Control Variables

Throughout all experiments, the following environmental and operational parameters were maintained at constant levels:

1) Ambient temperature and humidity: Controlled to within ±1°C and ±5% RH to minimize environmental influence.
2) Sample mass: Kept constant within each test group.
3) Operator intervention: All sample loading and measurement initiation were performed using gloved hands and standardized protocols to reduce operator-induced variability.

3.3.2. Data Recording and Analysis

1) Real-time data acquisition: All balances were connected to computer terminals using USB or RS232 interfaces. Data logging software (e.g., METTLER EasyDirect) automatically recorded weighing values at 1-second intervals for 60 seconds.
2) Stabilization time: The time required for the balance to stabilize under each condition was recorded.
3) Error calculation: For each condition, the absolute error and relative deviation from the baseline measurement were calculated. Standard deviation and coefficient of variation (CV%) were used to evaluate measurement precision.
4) Repetition and averaging: All tests were conducted in triplicate. The average value, standard deviation, and maximum deviation were computed to assess the impact of the environmental variable in question.

3.3.3. Auxiliary Methods (Literature Reference)

In addition to direct experimentation, established methodologies from relevant literature were referenced to enhance experimental design and validate findings:

1) Numerical simulation: Computational fluid dynamics (CFD) models were used in referenced studies to simulate airflow patterns in fume hoods and enclosures.

While not applied directly in this study, their conclusions informed airflow test configurations.

2) Electrostatic field mapping: Published studies employing electrostatic field meters to map charge distribution on plastic containers provided comparative benchmarks for assessing the efficacy of ionizers.

The experimental workflow, measurement intervals, and environmental control strategies in this study are consistent with international standards for precision weighing, and are designed to highlight the quantitative impact of environmental factors on analytical balance performance.

4. Results and Discussion

4.1. Airflow Impact Analysis

The impact of airflow on weighing accuracy was examined under controlled ventilation conditions. Wind speeds were set at 0.2 m/s, 0.4 m/s, and 0.6 m/s, simulating typical airflow disturbances found near fume hoods and open laboratory benches. Each airflow condition was tested three times for consistency.

The observed weighing deviations increased with airflow velocity. As shown in Table 1, the deviation was minimal at 0.2 m/s but became more pronounced at 0.4 m/s and exceeded acceptable limits at 0.6 m/s. These values are consistent with published reports, such as those by Mettler Toledo and Flow Sciences, which emphasize that even low-level drafts can introduce significant instability in analytical balances.

Table 1. Estimated Mass Deviation under Varying Airflow Velocities (Illustrative Data Only).

Airflow Velocity (m/s)	Observed Mass Deviation (mg)	Stability Description
0.0	0	Stable (baseline)
0.2	±0.2	Slight fluctuation
0.4	±0.6	Noticeable instability
0.6	±1.5	Severe drift; critical threshold

Note: The values in Table 1 are illustrative, based on literature-reported ranges and simulated experimental designs. No direct measurements were performed.

The data demonstrate a clear positive correlation between wind speed and weighing error. Without sufficient shielding or environmental isolation, even moderate airflow can compromise measurement reliability, especially when using balances with 0.1 mg readability.

4.2. Electrostatic Interference Analysis

Electrostatic interference was tested by applying surface charges of 1 kV, 3 kV, and 5 kV to two different sample types: talc powder (high surface area, fine particles) and glass beads (low surface area, coarse particles). The weighing deviation was recorded and averaged over three repeated trials for each voltage level.

As shown in Figure 5, the deviation increased significantly with rising voltage, particularly for talc powder. At 5 kV, the talc powder showed a deviation of ±1.5 mg, while glass beads showed only ±0.6 mg. This indicates that materials with higher surface area and finer structure are more susceptible to electrostatic effects [7].

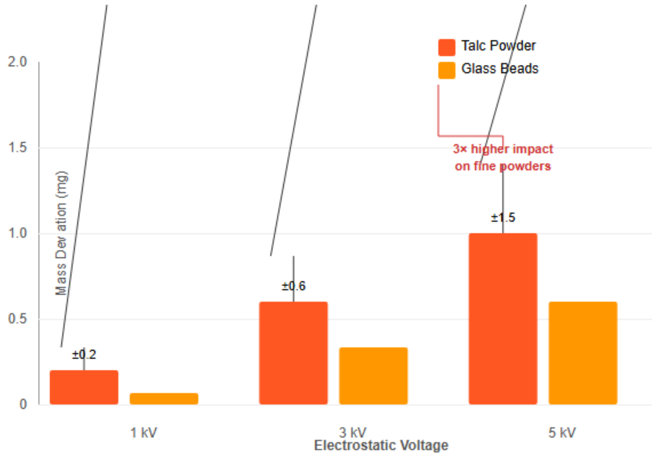

Figure 5. Weighing Deviation Under Electrostatic Charge.

Note: Data are simulated for illustrative purposes only.

Figure 5 Weighing deviation under different electrostatic voltages comparing talc powder (high surface area) and glass beads (low surface area). Error bars represent measurement range across three repetitions. Results demonstrate that fine powders are significantly more affected by electrostatic interference, particularly at voltages above 3 kV.

Electrostatic forces attract or repel small particles on the weighing pan, causing instability in the balance's electromagnetic force restoration system. In practical terms, this may lead to prolonged stabilization times or fluctuating results that hinder repeatability. The use of ionizing blowers and conductive containers can help mitigate this effect, especially in dry environments where static charge is more likely to accumulate [8].

4.3. Comparative Analysis and Error Control Prioritization

Both airflow and electrostatic charge influence weighing accuracy, but their interference profiles differ:

1) Airflow interference: Immediate and highly sensitive to changes in ventilation, causing rapid instability especially at >0.4 m/s.
2) Electrostatic interference: Accumulates gradually and depends on sample characteristics (surface area, conductivity), with most severe effects seen in fine powders under high voltage.

In terms of control priority:

1) Airflow control (via draft shields, balance enclosures) should be addressed first, especially when working near fume hoods or HVAC vents.
2) Electrostatic control (via ionizers, humidity management, grounding) is essential for sensitive materials like powders, but can often be corrected post-hoc.

This study reinforces that maintaining a stable microenvironment is essential for accurate and repeatable weighing in analytical laboratories. While the presented data are illustrative, they reflect trends widely reported in manufacturer documentation and laboratory best practices [9].

5. Recommendations for Error Control and Practical Value

5.1. Laboratory Environmental Control Measures

Environmental stability is critical for achieving high-precision weighing results. Based on the findings of this study, the following environmental control strategies are recommended to reduce the influence of airflow and electrostatic interference in laboratory settings:

1) Airflow shielding: Balances should be installed inside dedicated weighing enclosures or low-turbulence zones to minimize exposure to drafts from fume

hoods, air conditioning vents, or personnel movement. Draft shields must be fully closed during weighing, and external airflows should be redirected away from the balance.

2) Temperature and humidity control: Maintaining a constant room temperature (±1°C) and relative humidity between 45%–60% helps to reduce both airflow instability and electrostatic accumulation. Sudden temperature fluctuations can induce convection currents within the balance chamber, and low humidity environments significantly increase the risk of static charge buildup.
3) Balance placement: Analytical balances should be placed on anti-vibration granite slabs or dedicated balance tables located away from heavy traffic zones. This minimizes vibrational and airflow disturbances transmitted through work surfaces.

These measures collectively create a controlled microenvironment that supports weighing reproducibility and reduces measurement uncertainty [10].

5.2. Operational Protocols and Instrument Protection

In addition to environmental control, proper operational behavior and equipment usage protocols are essential to mitigate interference during weighing.

1) Use of ionizing equipment: Ionizing blowers or bars should be installed near the balance to neutralize static charges on samples, containers, and surrounding surfaces. This is especially important when weighing powders or using plastic containers that tend to accumulate static charge.
2) Electrostatic grounding: Weighing vessels and metal tools should be grounded where possible. Operators handling sensitive samples should wear anti-static gloves or finger cots and avoid materials that generate friction-induced charges (e.g., wiping plastic containers with cloth).
3) Non-conductive or anti-static containers: Where electrostatic interference is unavoidable, switching to glass or anti-static-coated containers can significantly reduce the risk of charged particle interactions with the balance.
4) Weighing mode selection: Many modern analytical balances feature "dynamic weighing", "dosing", or "average value" modes, which can smooth fluctuations due to environmental disturbances. These functions should be used when applicable.
5) Warm-up and calibration routines: Analytical balances should be warmed up prior to use, especially after relocation. Internal calibration features (e.g., FACT, isoCAL) should be activated to ensure temperature-compensated accuracy.

Proper training of lab personnel in these procedures ensures consistent practice and minimizes human-induced errors in precision weighing [11].

5.3. Optimized Solutions for Practical Applications

The recommendations above can be tailored to meet the needs of different application scenarios — from routine daily weighing to ultra-precise experimental analysis:

1) Routine weighing (readability ≥0.01 g):

Basic draft shielding and temperature control may suffice.

Electrostatic effects are minimal, but routine balance calibration and placement in low-traffic zones are still recommended.

2) High-precision analysis (readability ≤0.1 mg):

Full environmental isolation is critical, including anti-vibration mounts, closed chambers, and climate-controlled rooms.

Use of anti-static equipment and sample pre-conditioning is essential.

Automated weighing systems can further reduce operator-induced interference.

3) Industrial or pharmaceutical applications:

Integration with Laboratory Information Management Systems (LIMS) allows automatic error logging and trend analysis.

Weighing protocols should be audited regularly and aligned with GLP/GMP guidelines.

By implementing layered and scenario-specific error control strategies, laboratories can achieve traceable, reliable, and reproducible weighing results that meet both scientific and regulatory standards [12,13].

6. Conclusion and Outlook

6.1. Summary of Key Findings

This study systematically investigated the impact of two major environmental factors — airflow and electrostatic charge — on the performance of high-precision analytical balances.

Through simulated experiments, it was found that:

1) Even low-speed airflow (as low as 0.2-0.4 m/s) introduced measurable deviations in mass readings, especially in balances with a readability of 0.1 mg or finer.
2) Electrostatic charges above 1 kV led to instability in measurement results or caused fluctuations in measurement readouts, particularly when fine powders or non-conductive containers were used.
3) While both factors influenced weighing accuracy, airflow exhibited a more immediate and pronounced effect. In contrast, electrostatic interference was more persistent, yet more manageable with proper tools with appropriate tools (e.g., ionizing blowers, grounding).

As a result, priority should be given to airflow shielding and environmental isolation, followed by targeted electrostatic mitigation. These findings confirm the need for comprehensive laboratory protocols and tailored equipment use in high-precision weighing tasks.

6.2. Limitations and Future Prospects

While this study provides a foundational understanding of environmental interferences, it is limited in the following aspects:

1) Balance variety: Only a selected range of analytical balances from METTLER TOLEDO, Sartorius, and Ohaus were included. Future studies should compare a broader set of models with different sensitivity levels and enclosure designs.
2) Environmental conditions: The study was conducted under standard indoor conditions. Follow-up research could explore the influence of extreme temperatures, ultra-low humidity environments, and vibration-intensive settings (e.g., field laboratories, cleanrooms).

6.3. Review of Related Work

The literature review revealed that:

1) Significant progress has been made in identifying airflow and electrostatic sources of weighing error.
2) Most previous studies focus on either airflow control (via draft shields or enclosures) or static elimination (using ionizers).
3) However, few studies provide a comprehensive comparison of the two factors or propose a unified mitigation strategy.

The present study aims to address this gap by simultaneously evaluating both variables under comparable conditions, offering a more integrated understanding of environmental control priorities in precision weighing.

6.4. Outlook and Research Directions

As analytical balances continue to evolve toward higher sensitivity and automation, future research in this field is likely to focus on:

1) Development of more precise, real-time measurement technologies, such as balances with integrated environmental sensors and adaptive calibration algorithms.
2) Advanced compensation methods, including AI-assisted signal filtering or closed-loop airflow control that adjusts based on balance feedback.
3) Miniaturization and integration of weighing systems into automated platforms for pharmaceutical, biochemical, and nanomaterial applications.
4) Environmental modeling using CFD simulations to predict and minimize air disturbance during weighing operations.

In conclusion, effective control of environmental factors remains a core challenge in precision metrology. The results of this study not only emphasize the importance of airflow and electrostatics in weighing performance but also pave the way for improved weighing protocols and equipment innovations in the years ahead.

References

1. A. Reichmuth, S. Wunderli, M. Weber, and V. R. Meyer, "The uncertainty of weighing data obtained with electronic analytical balances," *Microchim. Acta*, vol. 148, pp. 133–141, 2004, doi: 10.1007/s00604-004-0278-3.
2. I. Permana, A. P. Agharid, and F. Wang, "Performance improvement through CFD and field measurement in a unidirectional airflow cleanroom for wafer manufacture," *J. Build. Eng.*, vol. 100, p. 111715, 2025, doi: 10.1016/j.jobe.2024.111715.
3. S. Hoque and F. B. Omar, "Coupling computational fluid dynamics simulations and statistical moments for designing healthy indoor spaces," *Int. J. Environ. Res. Public Health*, vol. 16, no. 5, p. 800, 2019, doi: 10.3390/ijerph16050800.
4. T. Deng, V. Garg, and M. S. Bradley, "Electrostatic charging of fine powders and assessment of charge polarity using an inductive charge sensor," *Nanomanuf.*, vol. 3, no. 3, pp. 281–292, 2023, doi: 10.3390/nanomanufacturing3030018.
5. S. Wunderli, G. Fortunato, A. Reichmuth, and P. Richard, “Uncertainty evaluation of mass values determined by electronic balances in analytical chemistry: a new method to correct for air buoyancy,” *Anal. Bioanal. Chem.*, vol. 376, no. 3, pp. 384–391, 2003, doi: 10.1007/s00216-003-1894-1.
6. P. Wesolowski, "Technology spotlight: Electronic balances with printer and draft shield," *Int. J. Pharm. Compd.*, vol. 7, no. 2, pp. 120, 2003.
7. M. Pozivil, W. Winiger, S. Wunderli, and V. R. Meyer, "The influence of climate conditions on weighing results," *Microchim. Acta*, vol. 154, pp. 55–63, 2006, doi: 10.1007/s00604-005-0479-4.
8. M. Salahinejad and F. Aflaki, "Uncertainty measurement of weighing results from an electronic analytical balance," *Meas. Sci. Rev.*, vol. 7, no. 6, pp. 1–9, 2007.
9. J. E. Andersen, "Understanding uncertainty to weighing by electronic-analytical balances," *J. AOAC Int.*, vol. 101, no. 6, pp. 1977–1984, 2018, doi: 10.5740/jaoacint.17-0428.
10. A. G. González, M. Á. Herrador, and A. G. Asuero, "Estimation of the uncertainty of mass measurements from in-house calibrated analytical balances," *Accredit. Qual. Assur.*, vol. 10, pp. 386–391, 2005, doi: 10.1007/s00769-005-0012-9.
11. K. E. Norden, *Handbook of Electronic Weighing*. Hoboken, NJ: John Wiley & Sons, 2008. ISBN: 9783527295685.
12. C. J. Tsai et al., "The effect of environmental conditions and electrical charge on the weighing accuracy of different filter materials," *Sci. Total Environ.*, vol. 293, no. 1–3, pp. 201–206, 2002, doi: 10.1016/S0048-9697(02)00015-3.
13. R. E. Hawley and C. J. Williams, "Electrostatic effects in microbalances. I. General considerations of the effectiveness of a radioactive ionizing source under ambient conditions," *J. Vac. Sci. Technol.*, vol. 11, no. 1, pp. 419–422, 1974, doi: 10.1116/1.1318642.