

Article

Decoupling Sensitivity and Recovery Kinetics of MOF/MWCNT-Based Gas Sensors Through Aerodynamic Chamber Design

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Abstract

This study investigates the aerodynamic trade-off between adsorption-driven sensitivity and desorption-driven recovery in MOF/MWCNT-based gas sensors. We compared two chamber designs: a Stable Flow Chamber (SFC) with streamlined laminar flow and a Disturbed Flow Chamber (DFC) featuring baffle-induced perturbations. Experimental results demonstrated that the SFC significantly enhanced sensitivity, showing increases of 16.3% (QCM), 21.1% (Resistive), and 53.8% (EIS) compared to the DFC, by promoting stable diffusion into the sensing layer. Conversely, the DFC markedly accelerated recovery kinetics, reducing recovery times by 10.3% (QCM), 12.3% (Resistive), and 55.9% (EIS), respectively, due to baffle-induced aerodynamic scrubbing. Computational fluid dynamics (CFD) confirmed that the DFC generates a 3.3 times higher wall shear stress even under a low Reynolds number regime ($Re \approx 2.3$). These findings establish that aerodynamic design can effectively decouple sensitivity and recovery kinetics, offering a route to optimize sensor performance without modifying materials.

Keywords: MOF/MWCNT composite; gas sensor; aerodynamic chamber design; mass transfer; sensitivity-recovery trade-off; CFD

1. Introduction

Indoor air quality (IAQ) is a critical determinant of health and well-being, particularly because people spend approximately 80–90% of their time indoors [1,2]. Indoor environments are influenced by multiple factors, including building materials, ventilation strategies, occupant activities, and outdoor pollutant infiltration [3]. Among various indoor contaminants, volatile organic compounds (VOCs), particulate matter (PM), and carbon dioxide (CO₂) have received considerable attention due to their direct links to adverse health outcomes [4–6]. In particular, VOCs emitted from paints, furnishings, and construction materials are strongly associated with sick building syndrome (SBS), respiratory irritation, and long-term health risks [7]. Furthermore, beyond general air quality management, the rapid detection of sudden concentration spikes is critical for hazardous gas leak detection in industrial or laboratory environments to ensure occupational safety [8].

Accurate and timely monitoring of indoor VOCs requires sensor platforms capable of detecting trace-level concentrations with high sensitivity and stable repeatability [9–11]. Among available sensing technologies, quartz crystal microbalance (QCM) sensors have been widely



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employed due to their high mass sensitivity, robustness, and real-time response [12,13]. By correlating resonance frequency shifts with mass adsorption on the crystal surface, QCM-based sensors provide a direct and quantitative method for gas detection, especially when combined with selective sensing layers [14,15]. In addition, solid-state electrical sensors, including chemiresistive and impedance-based devices, have been extensively investigated for VOC monitoring [16]. These sensors transduce chemical gas–solid interaction into distinct electrical responses, such as variations in resistance and impedance [17]. In particular, electrochemical impedance spectroscopy (EIS) offers valuable insights into charge transport and diffusion processes within porous sensing layers, making it highly sensitive to gas adsorption dynamics [11,18].

To further improve sensitivity and selectivity, recent gas sensor research has largely focused on the development of advanced sensing materials with high surface area and tailored chemical affinity. Metal–organic frameworks (MOFs), especially when integrated with conductive nanomaterials such as multi-walled carbon nanotubes (MWCNTs), have attracted significant interest due to their tunable pore structure, large adsorption capacity, and improved electrical conductivity [19–21]. While such material-centered approaches have successfully lowered detection limits and amplified sensor responses, they often treat the sensing environment as a fixed background condition. In practical sensor operation, however, the transport of analyte molecules from the bulk gas phase to the sensing layer is strongly governed by the local flow field and aerodynamic boundary conditions within the sensing chamber [22,23]. These fluid dynamic factors directly control the thickness and stability of the boundary layer, which in turn regulate mass transfer rates and adsorption kinetics at the sensor surface.

Under the low Reynolds number conditions, typical of gas sensor operation, flow within sensing chambers is predominantly laminar [24,25]. In such regimes, mass transfer is largely diffusion-dominated and is highly sensitive to boundary layer stability [26,27]. A stable laminar flow can sustain a relatively thick diffusion layer, allowing analyte molecules sufficient residence time to penetrate into the sensing layer and establish adsorption equilibrium. Conversely, flow disturbances or geometric perturbations can increase local shear stress and thin the boundary layer, thereby enhancing convective mass transfer but potentially disrupting adsorption stability [28]. Although chaotic advection has been proposed to enhance mixing even under laminar flow conditions [29,30], its net effect on sensor sensitivity and recovery kinetics, particularly for porous sensing layers, remains insufficiently understood so far.

Despite the clear physical relevance of flow-induced mass transfer, most gas sensor studies employ generic test chambers without explicitly considering how aerodynamic design influences sensing kinetics [31,32]. As a result, the trade-off between adsorption-driven sensitivity and desorption-driven recovery has rarely been examined in a systematic manner. This limitation hinders the rational design of sensor systems, especially for applications that require both high sensitivity and rapid cyclic operation.

The aim of this study is to elucidate the relationship between aerodynamic flow conditions and the kinetic performance of MOF/MWCNT-based gas sensors under laminar flow. To this end, two sensing chambers with distinct aerodynamic characteristics, a stable flow chamber (SFC) and a disturbed flow chamber (DFC), were designed to generate contrasting boundary layer conditions while operating within a comparable low Reynolds number regime. By combining computational fluid dynamics (CFD) simulations with experimental measurements using QCM, resistive, and impedance-based sensors, this study examines how chamber-induced flow variations influence sensitivity and recovery behavior without modifying sensing materials. Through this approach, the present work seeks to provide practical insights into the role of chamber aerodynamics in gas sensor performance.

2. Materials and Methods

2.1. Fabrication of Aerodynamic Sensing Chambers

Two types of gas sensing chambers with distinct aerodynamic characteristics were designed to investigate the influence of low Reynolds number flow conditions on sensor performance. Detailed geometries of the two chambers are illustrated in Figure 1. Both chambers were fabricated using a fused deposition modeling (FDM) 3D printer (Single Plus 3DP-310F, Cubicon Inc., Seongnam, Republic of Korea) to ensure reproducibility and geometric precision. Polylactic acid (PLA) was selected as the construction material based on its chemical stability and suitability for short-term VOCs exposure tests, as reported in a previous study [33]. The SFC was designed with a streamlined internal geometry to maintain a uniform and undisturbed laminar flow over the sensor surface. In contrast, the DFC incorporated zig-zag baffles positioned directly above the sensor to introduce controlled flow perturbations and increase local shear stress. Despite the geometric difference, both chambers were operated under comparable low Reynolds number conditions, ensuring that the flow regime remained laminar throughout the experiments.

2.2. Preparation of MOF/MWCNT-Based Gas Sensors

MOF/MWCNT-based gas sensors were prepared to evaluate the influence of aerodynamic chamber design on sensing kinetics. Figure 1 illustrates the architecture and configuration of the fabricated sensors used in this study, including mass-sensitive and electrical sensing platforms. Three representative MOFs (i.e., ZIF-8, Cu-BTC, and UiO-66) were selected due to their well-established adsorption characteristics and compatibility with composite sensor fabrication. The detailed procedures for material synthesis, sensor fabrication, and configuration were adopted from a previous study [34].

Briefly, the MOF/MWCNT composites were synthesized via sonochemical (for ZIF-8 and Cu-BTC) and solvothermal (for UiO-66) methods to ensure high crystallinity and uniform dispersion. The prepared suspensions were deposited onto the sensor substrates using an airbrush spray (Tamiya, Shizuoka, Japan) to achieve reproducible sensing layers. The coating thickness was controlled and verified by SEM analysis to be approximately $<10\ \mu\text{m}$.

For mass-sensitive measurements, the ZIF-8/MWCNT composite was deposited onto 5 MHz QCM crystals (Stanford Research Systems, Sunnyvale, CA, USA). For electrical sensing measurements, Cu-BTC/MWCNT and UiO-66/MWCNT composites were deposited onto interdigitated electrode (IDE) chips (O-discovery store, Yiwu, China) featuring 15 gold fingers with a gap of $50\ \mu\text{m}$. These sensors were connected to a multimeter (EDU34450A, Keysight, Santa Rosa, CA, USA) and an impedance analyzer (ZIVE SP1, WonA Tech, Seoul, Republic of Korea), respectively. For the impedance-based sensors, electrochemical impedance spectroscopy (EIS) measurements were initially explored over a frequency range of 0.1 Hz to 1 MHz with amplitudes from 10 mV to 250 mV. Based on the optimization, dynamic sensing was conducted at a fixed frequency of 1 Hz with an AC amplitude of 250 mV to maximize the signal-to-noise ratio. This sensor configuration allowed the evaluation of chamber-induced flow effects across different transduction mechanisms while maintaining consistent sensing material composition.

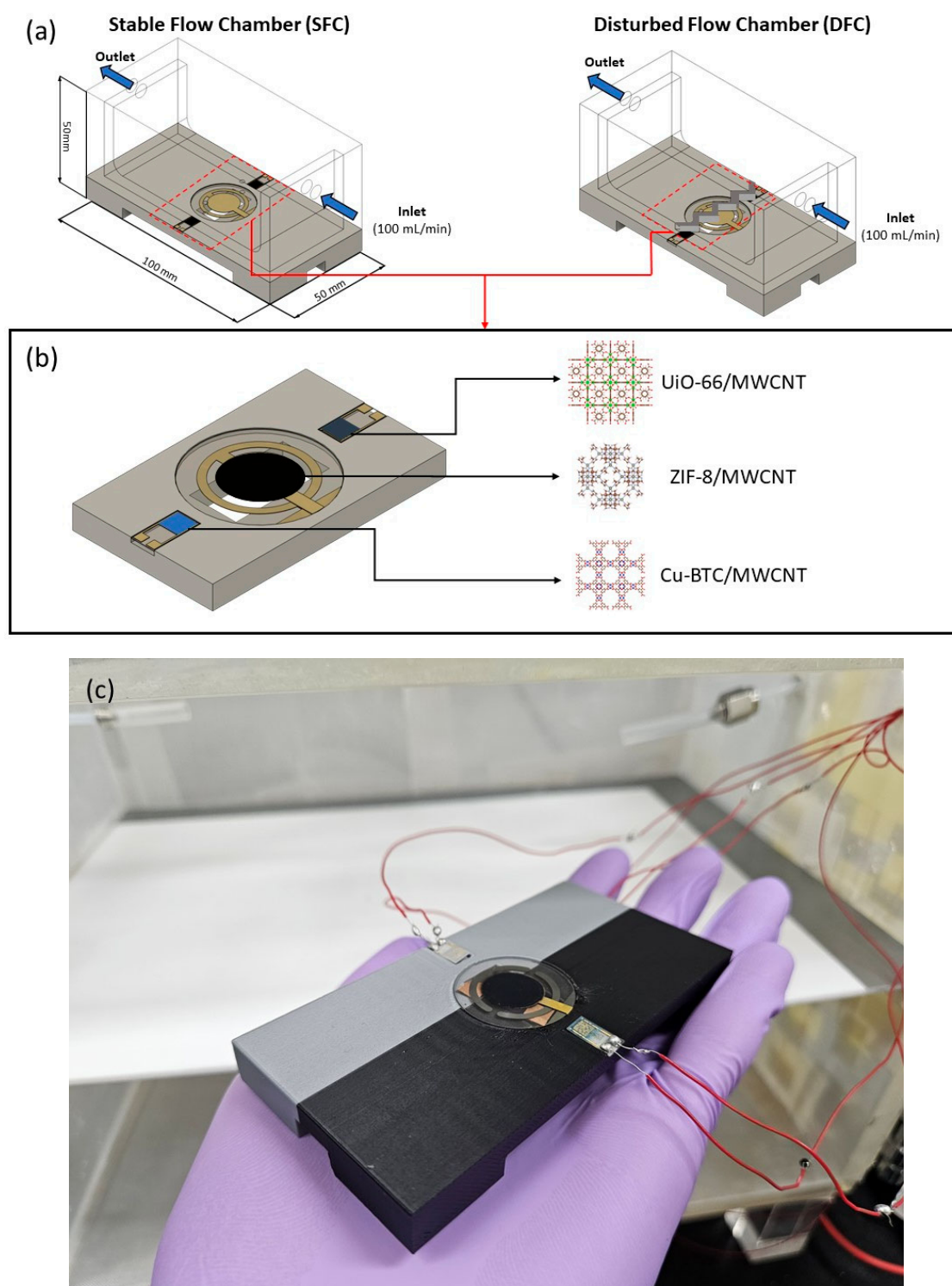


Figure 1. Schematic overview of the integrated aerodynamic sensing platform. (a) 3D illustrations of the sensing chambers: the Stable Flow Chamber (SFC) designed for uniform laminar flow and the Disturbed Flow Chamber (DFC) featuring zig-zag baffles (3 mm × 3 mm) to induce controlled flow perturbation. Blue arrows indicate the gas flow direction from inlet to outlet, and the specific mounting position of the sensor is highlighted at the center of the channel floor. (b) Detailed architecture of the MOF/MWCNT composite sensors installed at the indicated position: ZIF-8/MWCNT on QCM, Cu-BTC/MWCNT on resistive IDE, and UiO-66/MWCNT on impedance IDE. The internal dimensions of both chambers (length × width × height: 90 × 40 × 5 mm³) were kept identical to ensure comparable residence times. (c) Photograph of the actual sensor assembly, showing the relative scale of the MOF/MWCNT sensor chip mounted within the channel.

2.3. Gas Sensing Measurement Setup and Protocol

Gas sensing experiments were conducted using a custom-built experimental platform designed for controlled gas delivery and synchronized signal acquisition. A schematic overview of the integrated gas delivery and data acquisition system is shown in Figure 2. Dry zero air (99.9999% purity, Air Korea Co., Seoul, Republic of Korea) was used as the carrier gas to provide a stable baseline and to minimize interference from background contaminants. Benzene was selected as the model analyte due to its relevance as a representative indoor VOC. A benzene concentration of 1 ppm was generated by injecting liquid benzene into the carrier gas stream using a high-precision syringe pump (InfusionONE, New Era Pump Systems, Inc., Farmingdale, NY, USA). The injected liquid was immediately vaporized within a heated (80 °C) transfer line to ensure complete phase transition and uniform mixing with the carrier gas. The total gas flow rate was maintained at 100 mL/min using mass flow controllers (MFCs) (i-300CV-S2, Factors Co., Ltd., Daejeon, Republic of Korea), providing consistent operating conditions and ensuring that both sensing chambers operated within a comparable low Reynolds number regime ($Re = 2.3$). With an internal chamber volume of 18 mL and a flow rate of 100 mL/min, the nominal chamber residence time is ~ 10.8 s. This value is substantially shorter than the measured sensor response times ($T_{90} = 88\text{--}146$ s), indicating that the response dynamics are not limited by gas exchange in the chamber.

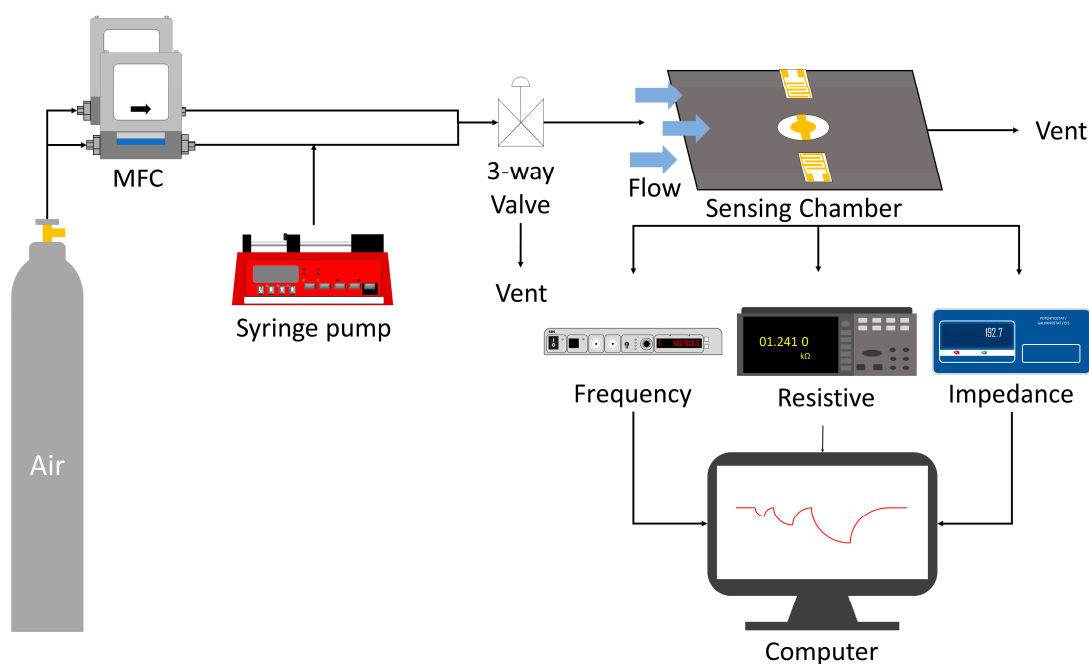


Figure 2. Schematic diagram of the integrated experimental platform for multi-modal gas sensing, highlighting the gas delivery system equipped with MFCs and a high-precision syringe pump for regulated analyte vaporization and delivery at a constant flow rate, interfaced with a synchronized data acquisition system for simultaneous monitoring of sensor frequency, resistance, and impedance.

All sensing measurements were performed following a fixed exposure–recovery protocol. Each sensing cycle consisted of three sequential steps: (i) baseline stabilization under dry zero air for 1 min, (ii) exposure to 1 ppm benzene for 2 min, and (iii) recovery under dry zero air (99.9999%) for 5 min. This cycle was repeated ten times for each sensor–chamber configuration to evaluate response repeatability and statistical reliability. Sensor signals were recorded continuously throughout the measurement cycles. For QCM sensors, frequency shifts were monitored to quantify mass adsorption. For resistive sensors, changes

in electrical resistance were recorded, while EIS measurements were performed to capture impedance variations associated with gas adsorption and desorption. All sensor responses were normalized to their respective baseline values to enable direct comparison across different transduction modes and chamber configurations. The experimental protocol and operating conditions were kept identical for both chambers. This approach ensured that any observed differences in sensitivity, response or recovery behavior could be attributed primarily to chamber-induced aerodynamic effects.

2.4. Computational Fluid Dynamics Simulation

CFD simulations were conducted to analyze the aerodynamic characteristics and flow-induced mass transfer behavior within the sensing chambers. The simulations were performed using Autodesk CFD 2026, employing the same chamber geometries using the experimental setup (Figure 2). This approach ensured direct correspondence between simulated flow fields and experimentally observed sensor performance.

Given the low flow rate employed in the gas sensing experiments, a laminar flow model was adopted. The gas phase was treated as an incompressible Newtonian fluid, and steady-state simulations were performed by solving the continuity equation and the incompressible Navier–Stokes equations. Air properties at ambient temperature and pressure were used for all simulations. A uniform velocity inlet corresponding to a total flow rate of 100 mL/min was applied at the chamber inlet, while a 0 gauge pressure condition (0 Pa), corresponding to the ambient atmospheric pressure, was imposed at the outlet. All chamber walls were treated as no-slip boundaries. To represent rapid adsorption at the sensor surface without explicitly resolving surface kinetics or species transport, the sensor surface was modeled as a perfect sink. This boundary condition enabled qualitative interpretation of flow-induced mass transfer behavior based on velocity fields, wall shear stress, and boundary layer characteristics.

3. Results and Discussion

3.1. Sensor Performance: Sensitivity and Recovery Kinetics

3.1.1. Dynamic Response and Repeatability

Prior to evaluating the sensing performance, baseline stability was examined to ensure that the sensor responses originated solely from analyte adsorption rather than flow-induced pressure or shear stress fluctuations. As shown in Figure 3, when exposed to pure carrier gas (dry zero air) at a flow rate of 100 mL/min prior to benzene injection, all sensors maintained a stable baseline with negligible signal variations (Resistivity change ≈ 0 , Frequency change ≈ 0). This result confirms that the aerodynamic forces with the carrier gas do not induce false-positive responses.

Upon subsequent exposure to 1 ppm benzene, all sensing platforms exhibited distinct and rapid dynamic responses. In the SFC, the QCM sensor displayed a maximum normalized frequency shift ($\Delta f/f_0$) of approximately 2.06×10^{-6} , indicating substantial mass uptake of benzene molecules. Consistently, the resistive (RS) and EIS sensors showed pronounced signal modulations, with peak normalized changes of 1.32×10^{-3} ($\Delta R/R_0$) and 8.52×10^{-4} ($\Delta |Z| / |Z|_0$), respectively (Table 1). These reproducible and well-defined responses across multiple transduction modes demonstrate the high sensitivity of the MOF/MWCNT composite toward trace-level benzene. Moreover, the stable baseline and sharp signal evolution validate the reliability of the sensor platform, providing a robust foundation for subsequent investigation of sensitivity enhancement and recovery kinetics.

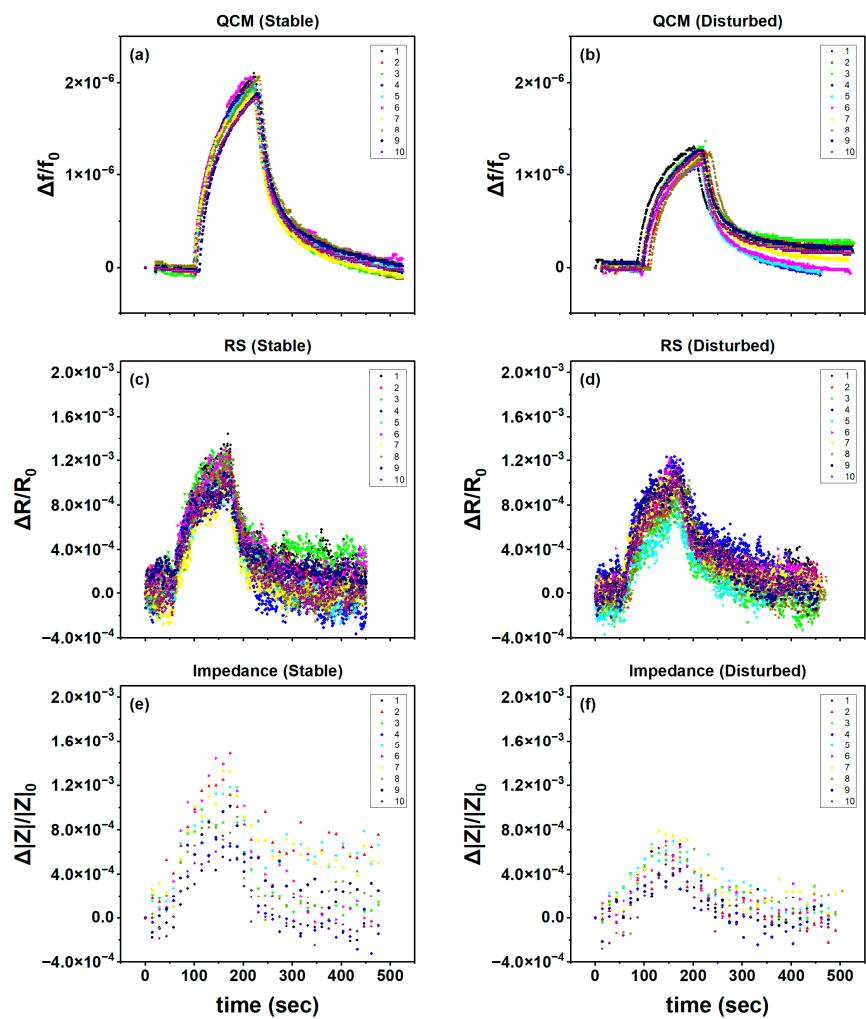


Figure 3. Comparative dynamic response profiles and cyclic repeatability (N = 10) of MOF/MWCNT composite sensors under 1 ppm benzene exposure. (a,c,e) Sensing performance in the Stable Flow Chamber (SFC) for QCM ($\Delta f/f_0$), resistive ($\Delta R/R_0$), and impedance ($\Delta |Z|/|Z|_0$) modes, respectively; (b,d,f) corresponding sensing results in the Disturbed Flow Chamber (DFC). The color-coded indices (1–10) correspond to the cycle number, utilizing a consistent color scheme across all plots to visualize repeatability. The SFC exhibits superior sensitivity through stable adsorption, while the DFC demonstrates accelerated recovery kinetics and enhanced baseline consistency due to aerodynamic scrubbing.

Table 1. Summary of Sensor Performance Characteristics (Mean $\pm$ SD, N = 10).

Sensor	Metric	SFC	DFC
QCM	Max Response ($\Delta f/f_0$)	$2.06 \times 10^{-6} \pm 7.96 \times 10^{-8}$	$1.77 \times 10^{-6} \pm 2.06 \times 10^{-7}$
	Response Time (T_{90})	88.13 ± 2.52 s	92.34 ± 3.12 s
	Recovery Time (T_{rec})	128.52 ± 5.18 s	115.24 ± 4.76 s
RS	Max Response ($\Delta R/R_0$)	$1.32 \times 10^{-3} \pm 1.05 \times 10^{-4}$	$1.09 \times 10^{-3} \pm 1.25 \times 10^{-4}$
	Response Time (T_{90})	142.38 ± 15.39 s	146.10 ± 17.54 s
	Recovery Time (T_{rec})	94.19 ± 38.99 s	82.63 ± 24.38 s
EIS	Max Response ($\Delta Z / Z _0$)	$8.52 \times 10^{-4} \pm 1.21 \times 10^{-4}$	$5.54 \times 10^{-4} \pm 1.48 \times 10^{-4}$
	Response Time (T_{90})	110.43 ± 45.21 s	86.45 ± 12.11 s
	Recovery Time (T_{rec})	163.29 ± 9.88 s	72.04 ± 8.35 s

3.1.2. Decoupling Sensitivity and Recovery

The comparative analysis of the kinetic parameters clearly demonstrates that the aerodynamic chamber design fundamentally alters sensor performance. Rather than providing a uniform performance enhancement, the two flow characteristics introduce a distinct trade-off between adsorption-driven sensitivity and desorption-driven recovery kinetics, thereby enabling their effective decoupling.

Across all sensing modalities, the SFC consistently yielded higher sensitivity. For the QCM sensor, the normalized frequency change reached 2.06×10^{-6} , approximately 16.3% higher than the value obtained in the DFC (1.77×10^{-6}). Likewise, the resistive sensor exhibited a stronger signal in the SFC ($\Delta R/R_0 = 1.32 \times 10^{-3}$) than the DFC (1.09×10^{-3}). This enhancement indicates that the stable boundary layer allows more benzene molecules to remain near the sensor surface for extended periods, thereby promoting effective adsorption onto the MOF layer. A similar trend was observed for the EIS sensor, where the response in the SFC (8.52×10^{-4}) exceeded that in the DFC (5.54×10^{-4}) by 53.8%. Because impedance-based sensing is particularly sensitive to changes in internal pore occupancy, these results suggest that the SFC facilitates diffusion into the deep micropores of the MOF structure. In contrast, flow perturbations in the DFC disrupt the concentration in the boundary layer and limit equilibrium pore filling.

In contrast to the adsorption behavior, the DFC exhibited a clear kinetic advantage during the desorption phase. The recovery time (T_{rec}) of the EIS sensor was reduced to approximately 72 s in the DFC, compared to ~163 s in the SFC (Table 1). A consistent reduction was also recorded for the resistive sensor, which recovered in approximately 83 s in the DFC compared to 94 s in the SFC. This pronounced reduction confirms that baffle-induced aerodynamic scrubbing rapidly lowers the local partial pressure of benzene at the sensor surface. As a result, desorbed molecules are efficiently removed from the vicinity of the sensing layer, suppressing re-adsorption and accelerating signal recovery.

The dependency of sensor kinetics on gas penetration depth is supported by previous studies utilizing supersonic molecular beams (SMB) or high-speed gas switching systems [35,36]. These works demonstrate that controlling incident gas momentum is crucial for distinguishing intrinsic diffusion kinetics from boundary layer effects. To verify this theoretically, we estimated the Knudsen diffusion coefficients (D_K) for benzene within the micropores of our MOF materials (UiO-66, ZIF-8, and Cu-BTC). The calculated D_K values range from 5.7×10^{-8} to 1.2×10^{-7} m²/s, depending on the pore size ($d_p \approx 6.0$, 7.6, and 9.0–13.0 Å for UiO-66, ZIF-8, and Cu-BTC, respectively). These values are orders of magnitude lower than the bulk diffusion coefficient in air ($\approx 10^{-5}$ m²/s), confirming that slow internal diffusion is the rate-determining step. This finding substantiates that the aerodynamic scrubbing effect of the DFC mode effectively accelerates the recovery phase by maximizing the concentration gradient across the sensing layer.

3.1.3. Cyclic Repeatability and Reliability

To evaluate sensor reliability and operational stability, ten consecutive adsorption–desorption cycles were performed under identical experimental conditions (Figure 3). Sensors operated in both chamber configurations exhibited highly reproducible response profiles with stable baselines throughout the cycling tests, indicating that neither flow induces analyte accumulation nor memory effects over repeated operation.

Despite the comparable repeatability observed in both designs, a clear difference emerged in the recovery behavior. Sensors operated in the DFC consistently displayed steeper desorption profiles and faster signal recovery. As summarized in Table 1, the average recovery time was reduced by approximately 55% compared to that obtained in the SFC. This behavior reflects the role of baffle-induced aerodynamic scrubbing, which

rapidly removes desorbed benzene molecules from the vicinity of the sensing surface and suppresses re-adsorption during the recovery phase.

3.2. Aerodynamic Analysis via CFD

To understand the physical mechanisms underlying the experimentally observed trade-off between sensitivity and recovery kinetics (Section 3.1), CFD simulations were conducted to analyze the aerodynamic characteristics and flow-induced mass transfer behavior within the sensing chambers.

Figure 4 summarizes the CFD-simulated velocity fields and flow patterns for both chamber designs. In the SFC, this concentration gradient is preserved within a highly quiescent aerodynamic environment (Figure 4a,c). Analysis of the vertical cross-section above the sensor shows that the flow is predominantly horizontal, with an average streamwise velocity of $V_x \approx 7.47$ mm/s (obtained from Figure 4a) and a negligible vertical velocity component ($V_z \approx 0.0024$ mm/s). Consistent behavior is observed on the horizontal plane, where a moderate velocity $V_x \approx 4.54$ mm/s (obtained from Figure 4c) and a consistent negative static pressure (-0.069 Pa) are maintained. Surface analysis further confirms this stability, revealing a nearly uniform static pressure (~ 0.021 Pa) and a low average wall shear stress of 2.29×10^{-4} Pa. The absence of significant vertical momentum places the SFC in a low Sherwood number (Sh) regime, where the concentration boundary layer remains largely undisturbed and mass transfer is dominated by diffusion rather than convection [27]. Under these conditions, gas molecules remain near the sensor surface for prolonged periods, allowing steady diffusion into the deep micropores of the MOF layer and promoting adsorption toward near-thermodynamic equilibrium [14].

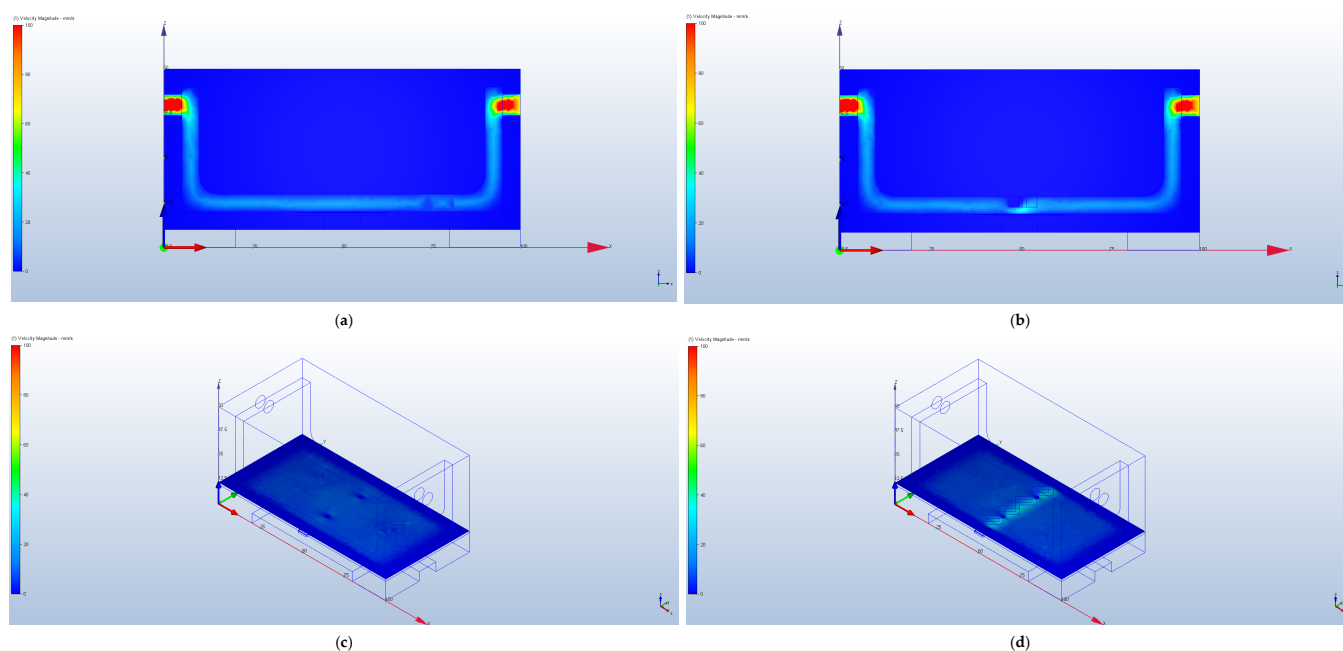


Figure 4. CFD simulation results illustrating velocity magnitude and flow characteristics in different chamber designs. (a) Front cross-sectional view of the SFC, showing a streamlined laminar flow with minimal vertical momentum; (b) Front cross-sectional view of the DFC, highlighting baffle-induced vertical momentum and flow perturbation; (c) Velocity magnitude distribution on the horizontal plane of the SFC, illustrating a spatially uniform velocity field; and (d) Velocity magnitude distribution on the horizontal plane of the DFC, demonstrating localized high-velocity jets and aerodynamic scrubbing near the sensor surface.

In contrast, the DFC exhibits significant aerodynamic scrubbing, characteristic of a high Sh regime even under laminar flow conditions (Figure 4b,d). Vertical cross-section

reveals a substantial vertical velocity component ($V_z \approx 1.55$ mm/s) accompanied by a high-velocity horizontal jet ($|V_x| \approx 6.86$ mm/s) [37]. The horizontal plane shows an increased average velocity ($|V_x| \approx 5.27$ mm/s) together with a significant static pressure buildup (0.27 Pa), approximately ten times higher than that observed in the SFC.

This enhanced vertical momentum originates from baffle-induced flow impingement, which increases the average wall shear stress to 7.60×10^{-4} Pa, approximately 3.3 times higher than that of the SFC. While such conditions enhance convective mass transfer at the sensor surface, they effectively thin the diffusion boundary layer and disrupt the stable concentration gradient required for deep pore penetration. Consequently, adsorption in the DFC is dominated by near-surface interactions rather than equilibrium uptake within the MOF micropores.

Overall, the two chamber modes provide complementary advantages rather than a single universally superior option. The SFC is preferable when trace-level detection and maximum adsorption uptake are required (e.g., indoor air quality monitoring), where stable laminar flow supports longer residence near the sensing layer and promotes pore filling. By contrast, the DFC is preferable when rapid reuse and short-cycle measurements are needed (e.g., leak detection or alarm-oriented monitoring), where baffle-induced aerodynamic scrubbing assists fast clearance of residual molecules and shortens recovery.

4. Conclusions

This study demonstrates that aerodynamic chamber design plays a crucial role in governing the performance of MOF/MWCNT composite gas sensors. By decoupling flow stability and mixing-induced perturbations, the present work shows that adsorption-driven sensitivity and desorption-driven recovery kinetics can be independently regulated through geometric control of a flow chamber.

The experimental results revealed a fundamental trade-off in sensor performance: during gas exposure, a stable boundary layer prolonged molecular residence near the sensing surface and supported inward diffusion into MOF micropores, thereby promoting adsorption and improving sensitivity. By contrast, baffle-induced aerodynamic scrubbing accelerated recovery by rapidly lowering the local analyte partial pressure at the sensor surface, which favors outward diffusion (desorption) once the gas supply is terminated. This recovery enhancement was consistently observed across mass-sensitive, resistive, and impedance-based transduction modes, suggesting that aerodynamic scrubbing serves as a general physical driver for rapid sensor regeneration.

These sensing behaviors are attributed to the aerodynamic characteristics identified in the simulation. Even under a low Reynolds number regime ($Re \approx 2.3$), the introduction of baffles increased the wall shear stress by approximately 3.3 times, establishing a convection-enhanced environment without inducing turbulence. These findings establish aerodynamic flow engineering as an effective strategy for decoupling sensitivity and recovery kinetics, providing a rational design framework for gas sensors that require both high sensitivity and fast recovery.

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