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Research Article

Analysis of the Applicability of Tesla Valve Geometry Design Manufactured by Polymer 3D Printing for Silencer in 5.56-mm Caliber Rifle

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Abstract: Sound dampers are vital in modern weapon systems, particularly for military applications. Conventional silencers typically employ simple expansion chamber baffles, which have limitations in damping efficiency and production flexibility due to their metal construction. This study explores the application of the Tesla valve concept, which is traditionally used for fluid flow control, as an alternative gas suppression system for firearms. A 5.56 mm caliber firearm inner silencer was designed based on Tesla valve geometry using CAD and fabricated using the fused deposition modeling method with ABS-GF material. Experimental tests were conducted with five shots per design variation, measuring sound pressure level (SPL) and bullet velocity, while SPL data were analyzed using the signal-to-noise ratio (SNR) method. The two-partition Tesla valve design achieved the highest SPL reduction of 7.03 dB, although it decreased the bullet velocity by 63.38 m/s. This study demonstrates the feasibility of combining Tesla valve geometry with 3D-printed materials to create lightweight, efficient, and rapidly producible firearm silencers. These findings provide valuable insights for developers and manufacturers to explore alternative silencer designs and anticipate future trends in passive sound suppression technology.

Keywords: 3D printing; Silencer; Tesla valve

1. Introduction

In recent decades, advances in military and security technology have led to various innovations in weapon systems, including supporting devices such as silencers. These devices are designed to reduce the sound of gunfire, conceal the shooter's position, and protect the user's hearing (Kilikevičius et al., 2023; Dewa et al., 2023). Studies have indicated that silencers can reduce peak sound pressure by 17–24 dB and A-weighted equivalent energy (LAeq) by 9–21 dB, depending on the type of firearm and ammunition used (Murphy et al., 2018). However, despite the significant reduction provided by silencers, the risk of hearing impairment remains, as analytical models indicate that shots from weapons such as the M16 generate shock waves that are sufficiently dangerous to hearing (Salomons, 2024). Another threat comes from propellant combustion products; firearms such as the M16 rifle can produce harmful compounds that contaminate the air around the user (Ase et al., 1985). Preliminary research also indicates that these combustion products can spread rapidly in enclosed environments and intensify health risks (Hakonen, 2011). Different bullet calibers exhibit distinct pressure and trajectory characteristics in ballistic studies, which influence the design of the sound suppressor used (Fayed et al., 2011; McCoy, 1985). Ballistic data also reveal aerodynamic differences between 5.56-mm bullets

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and other calibers, which further impact the suppressor's acoustic performance (Huerta-Torres et al., 2021; McCoy, 1985).

Additionally, accurate evaluation of silencer performance is critical. Clipping often occurs in measurement devices during data collection, necessitating signal recovery or declipping methods (Záviška et al., 2022; Ozerov et al., 2016). Crossfading techniques have also been proven to enhance the measurement validity of high-intensity audio events (Záviška et al., 2022). Conventional sound suppressor designs typically use holes in the diffuser, where acoustic damping is affected by variations in hole shape and angle (Gök et al., 2023). However, this type of suppressor tends to be large, heavy, and increases backpressure during rapid-fire, reducing weapon stability (Huerta-Torres et al., 2021). Although experimental studies have shown that cylindrical and canonical shapes produce different acoustic characteristics, no standard design has been identified as the most optimal (Dutta et al., 2017).

The application of Tesla valve geometry offers an innovative solution as an alternative. The Tesla valve is a one-way channel structure without moving parts, allowing low-resistance gas flow in one direction and blocking reverse flow with high resistance (Tesla, 1920). Structural parameters, such as deflection angle and channel width, significantly influence pressure damping (X. Zhang et al., 2024), and numerical studies support the effectiveness of this geometry in efficiently directing gas (Du et al., 2024). This concept provides reduced backpressure and efficient sound damping in the context of firearms (Wroblewski et al., 2023).

To fabricate such complex geometries, 3D printing technology is the primary solution (Chua et al., 2014). The FDM method enables precise printing of internal structures, with print speed and layer height affecting final strength (Bist et al., 2022). The ABS material reinforced with glass or carbon fibers demonstrates suitable wear resistance for high-pressure applications (Dhandapani et al., 2023). This technology is evolving with AI support for design optimization (Malashin et al., 2024) and potential sensor integration (Araújo et al., 2023). Furthermore, CAD and CAE technologies, including ANSYS Workbench and Gambit, play a crucial role in reducing development time and modeling fluid-based structures (Joshi, 2023; Maulana et al., 2024). Challenges in computational fluid dynamics simulation, such as turbulence model validation (Lain and Vidal, 2024) and sound pressure assessment (Rehman et al., 2011), are critical for refining designs. Structural analysis ensures durability (J. Zhang et al., 2023. Sinclair, 2023 proved that 3D-printed suppressors can significantly reduce noise levels, although material heat resistance remains a challenge.

Based on the background above, this research aims to: (1) design a 5.56 mm firearm inner silencer based on Tesla valve geometry using CAD; (2) fabricate the design using the FDM method with ABS-GF material; and (3) experimentally analyze the proposed design's acoustic performance (Sound Pressure Level) and ballistic impact (bullet velocity). This study offers a novel approach combining passive flow control with AM to address the limitations of conventional silencers.

2. Methods

2.1 Material

Filament material is the basic material used in 3D printing technology, particularly in the Fused Deposition Modeling (FDM) method. Filaments are usually thermoplastic polymers that are heated to a semi-liquid state and then formed into three-dimensional objects through a printer nozzle. The material used in this study was ABS-GF.

2.2 Inner Silencer Design

The dimensions of the inner silencer cover are adjusted for precise installation and optimal function. This study designs three inner silencer configurations: a Tesla valve without partitions, with two partitions, and with four partitions. The partitions divide the gas flow, with alternating Tesla valve directions at each section, to gradually slow the gas flow and dampen the sound without causing excessive backpressure. These variations are expected to identify the most effective configuration for sound suppression while maintaining the performance of the weapon. The designs are illustrated in Figure 1.

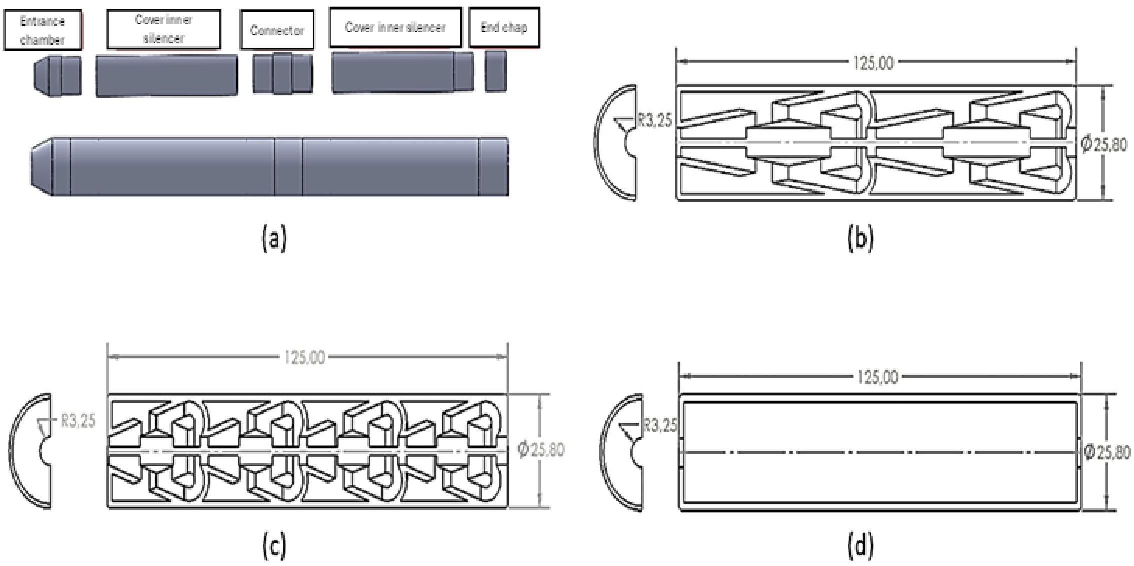

Figure 1 (a) Cover Silencer Design; (b) Tesla Valve with 2 Partition Design; (c) Tesla Valve with 4 Partition Design; (d) Tesla Valve without Partition Design

2.3 Firing Methods

The experimental testing was meticulously conducted to ensure safety and data accuracy..The firing process followed a step-by-step procedure as described below:

1. Site Preparation: The firing range was configured with a minimum distance of 30 m between the firearm and the embankment, strictly adhering to the MIL-STD-1474E standard.

2. Instrumentation Setup: The FPS meter was positioned 3 m in front of the barrel to measure the projectile's velocity, and the microphone and dB meter were placed 5 m away from the barrel at a 195° counterclockwise angle. The microphone was set at a height of 33 cm, facing upward, and aligned with the position of the prone shooter. Figure 2 shows the entire setup.

3. Calibration: All instruments were tested before live firing. The accuracy of the sound measurement device was verified through a clapping test using the OpenSoundMeter application (Figure 4). The average SPL recorded during this test was 121.88 dB. This value is consistent with the reference data when considering the A-weighted method (dB A), which adjusts for human hearing sensitivity.

4. Firing Execution: The testing used a 5.56 mm SS-2 V4 weapon with MU5-TJ ammunition. Five consecutive shots were fired for each design variation (without silencer, no partition, 2-partition, and 4-partition) to obtain representative measurement results using the SPL (peak) and A-weighted approaches (Wroblewski et al., 2023).

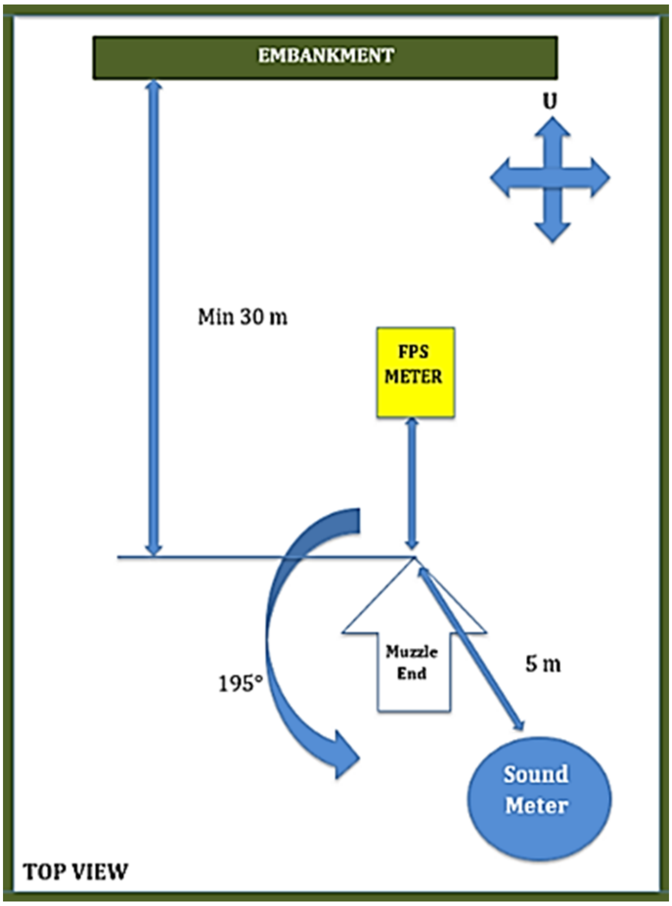

Figure 2 Location planning

3. Results and Discussion

3.1 3D printed results

The design was successfully created from ABS-GF filament using a 3D printer.FDM technology allows the production of complex Tesla valve geometry. Figure 3 shows the inner silencer before and after assembly. Once the printing process was completed, the joints of the product were coated with heat-resistant RTV sealant (Figure 3). This coating was applied to ensure that there were no leaks during the testing phase, thus maintaining the design integrity.

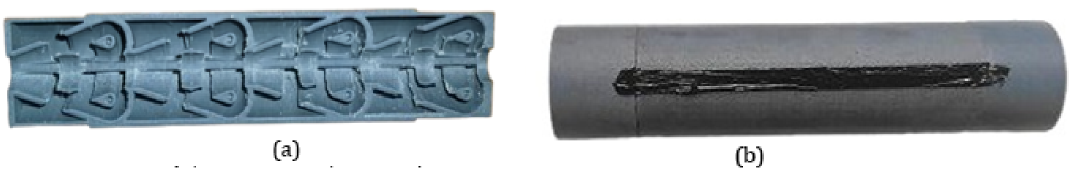

Figure 3 (a) Part of the 3D printed inner silencer result. (b) The two parts are assembled to form the inner silencer

3.2 Sound Meter Results

Complete data related to the average, standard deviation, and sound meter measurement results. Figure 4 presents the SPL measurement results for each silencer configuration as a line graph to illustrate the sequential trend across five consecutive shots. Although the dataset consists of only five discrete measurements, the use of a line graph emphasizes the progression of SPL values and makes it easier to identify dynamic variations, particularly the noticeable increase observed in shots 4 and 5. The higher SPL in these later shots is likely due to heat accumulation within the suppressor body, which causes temporary deformation of the polymer structure and reduces the effectiveness of the Tesla valve channels in redirecting gas flow. The testing results were further analyzed using the signal-to-noise ratio (SNR). All SNR values exceeded 60 dB and met the expected criteria. Detailed analysis results are shown in Figure 5.

As shown in Table 1, the 2-partition silencer achieved the highest decibel reduction of 7.03 dB compared with the unsilenced condition. Its superior performance is attributed to a wider flow chamber, allowing the Tesla valve to optimally utilize fluid inertia for sound dampening. In contrast, the narrower channels in the 4-partition design restrict gas flow, reducing its effectiveness.

Table 1 Average SoundMeter Results

No	Variation	Average (dB)	Standard Deviation (dB)	Standard Deviation (%)
1	Without Silencer	138.01	1.12	0.81
2	Silencer Partitioning Without	131.86	1.36	1.03
3	Silencer With 2 Partitions	130.98	2.42	1.85
4	Silencer With 4 Partitions	132.77	1.82	1.37

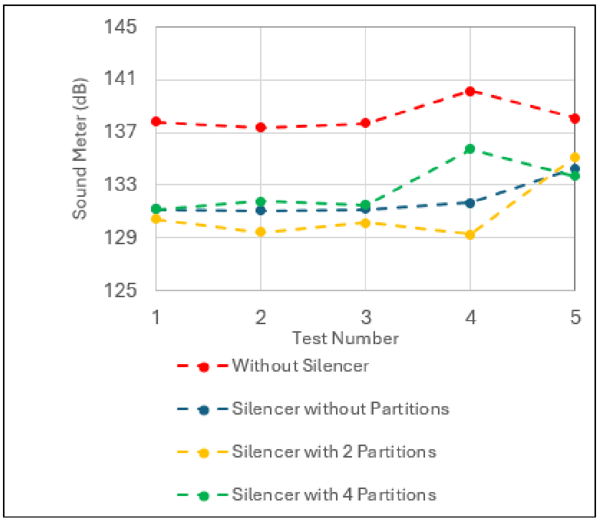

Figure 4 Graph of SoundMeter Measurement Results

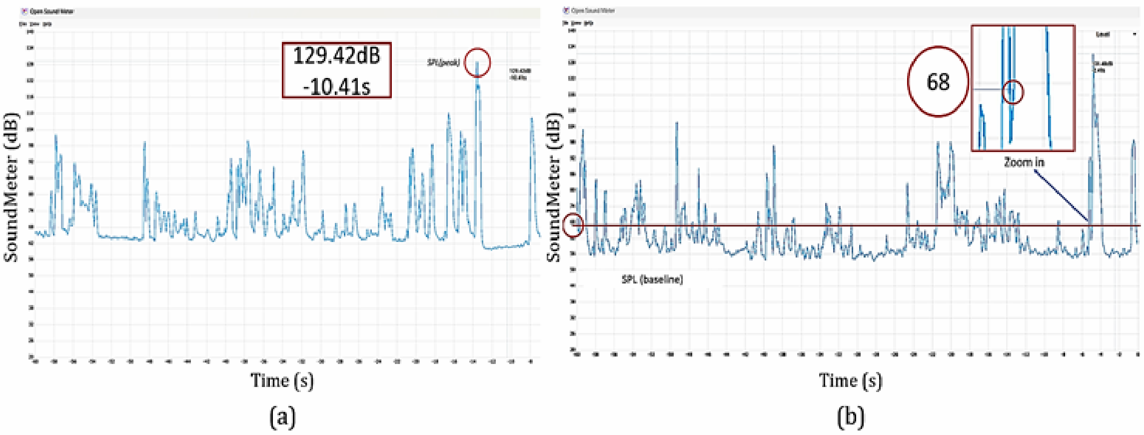

Figure 5 (a) SPL (peak) and (b) SPL (baseline) from the SoundMeter test results

3.3 FPS meter results and ballistic discussion

The results of this test prove that the use of a silencer can affect the bullet velocity.

Table 2 Average speed measurement results

No	Variation	Average (dB)	Standard Deviation (dB)	Standard Deviation (%)
1	Without Silencer	806.86	6.89	0.85
2	Silencer Without Partitioning	781.74	16.21	2.07
3	Silencer With 2 Partitions	743.48	16.61	2.23
4	Silencer With 4 Partitions	757.22	20.08	2.65

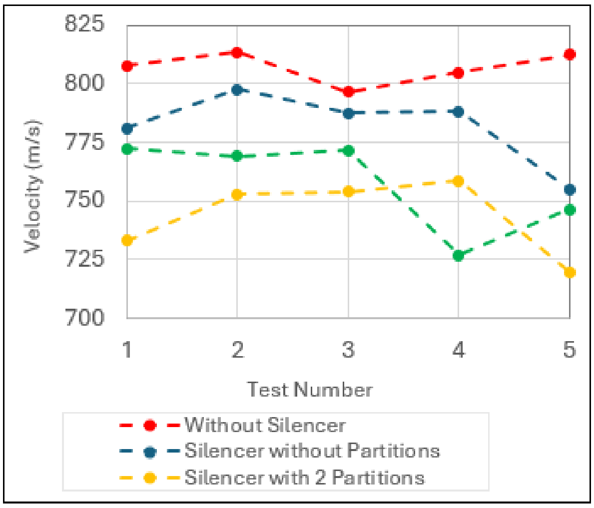

Figure 6 FPS meter measurement results

Increased gas pressure causes the reduction in projectile velocity, in line with Bernoulli's principle, where higher pressure leads to lower flow velocity. Inside the silencer, the gas pressure changes due to the partition, expansion chamber, and Tesla valve design, slowing the bullet as static pressure rises. Turbulent flow and energy losses also contribute to this velocity drop. The Tesla valve geometry induces turbulence through collisions between forward and reverse flows, generating vortices and uneven pressure that reduce the effectiveness of the bullet propellant gas. Overall, the test results show that the 2-partition silencer produced the lowest average projectile velocity (743.48 m/s). While effective in suppressing shock waves and noise, the partitions also reduced the velocity due to the increased internal resistance.

3.4 Condition of the Silencer after the Firing Test

Among the three silencers, the 4-partition design suffered the most damage after test firing due to higher turbulence from collisions between forward and reverse flows, causing trapped gas pressure to deform the structure. Damage in all designs was not caused by material limitations, as ABS-GF has superior properties, but rather by two factors: filament pattern direction during 3D printing and complex Tesla valve geometry.

The silencer damage is heavily influenced by the printing orientation. When the silencer is positioned upright during printing (transverse), the layer adhesion is weaker against the shot's axial force. Although the gas moves in all directions, the greatest force occurs axially. Previously, printing was attempted with a longitudinal orientation, but the support structure was not optimal due to the complicated design of the Tesla valve.

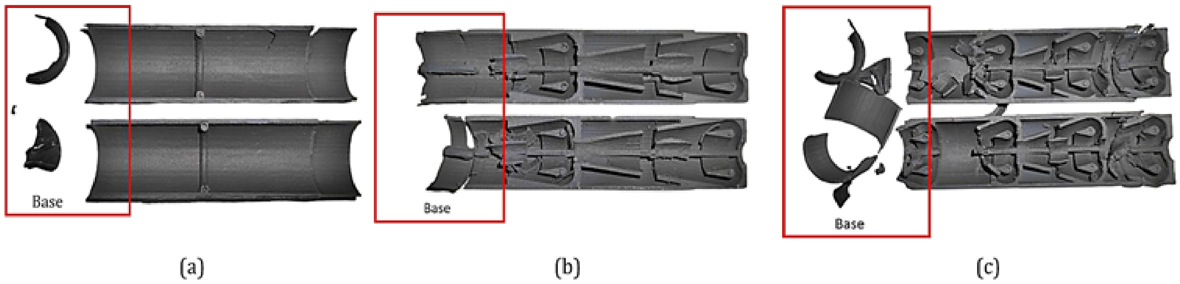

Figure 7 (a) Silencer without partition; (b) Silencer With 2 Partition; (c) Silencer with 4 partitions

Figure 8 compares the two build orientations applied during the printing process.The relative alignment between the part axis and the build direction (Z), as indicated by the arrows, is the key distinction. The part axis is parallel to the build direction in the longitudinal orientation (Figure 8a), whereas the part axis is perpendicular to Z in the transverse orientation (Figure 8b). Clarifying this alignment is essential for interpreting differences in strength and structural response under axial versus lateral loading because layer-by-layer fabrication yields direction-dependent mechanical behavior.

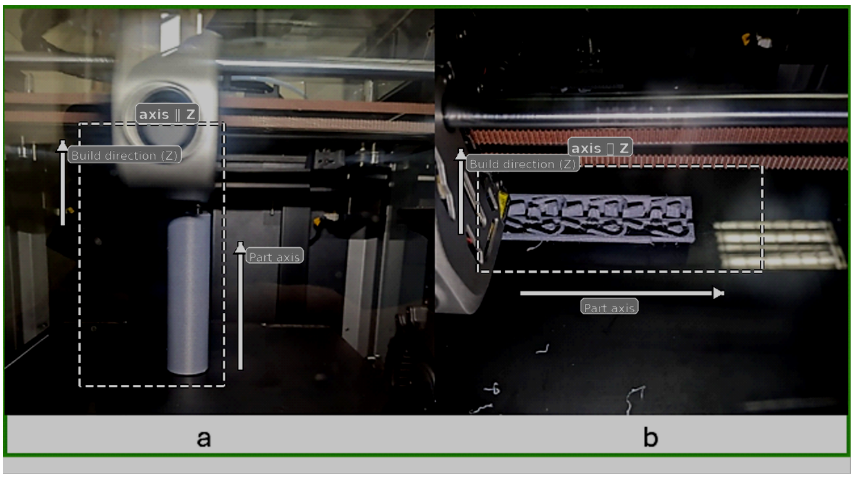

Figure 8 (a) Printing process with transverse orientation and (b) printing process with longitudinal orientation

4. Conclusions

This study successfully analyzed the applicability of Tesla valve geometry in 3D-printed silencers for 5.56 mm rifles using ABS-GF material.Several key conclusions can be drawn based on the experimental results and analysis:

The design of the Tesla valve was acoustically pleasing, indicating that passive flow control could potentially reduce the noise caused by supersonic gas expansion. The two-partition arrangement exhibited the highest overall performance among all analyzed setups, achieving an average Sound Pressure Level (SPL) of 130.98 dB. This represents a 7.03 dB reduction from the unsilenced state, indicating that the Tesla-valve-based internal mechanism may significantly diminish gunshot noise.

Hearing augmentation requires a ballistic trade-off. The intricate design of the internal pathways of the Tesla valve leads to heightened flow resistance and turbulence, thereby decelerating the projectile. The two-partition arrangement employed this strategy, with the lowest average velocity of 743.48 m/s.The projected velocity reduction was 63.38 m/s relative to the control group.

Fused Deposition Modeling (FDM) using ABS-GF is good for quick prototyping from a manufacturing and structural perspective. However, the results show that it does not last long when fired repeatedly. The way the printing was done These findings validate that Tesla valve geometry, traditionally used in microfluidics, can be adapted for high-pressure firearm suppression. However, future development must address the ballistic trade-off and structural durability by optimizing the printing orientation (longitudinal) or utilizing materials with higher thermal resistance.

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Author Contributions

FM contributed to the conceptualization, research planning, structural analysis, methodology, and supervision of the study. DED was responsible for the original draft, visualization, and editing. AHF contributed to the study's methodology, investigation, data curation, and validation. The RTD supported the experiment design, investigation, resources, and data collection. ANS contributed to the formal analysis, software, and computational support. HW supported the experimental setup, instrumentation, and data acquisition. MASH contributed to the validation, review and editing, and technical support. WC provided supervision, project administration, review and editing, and final manuscript approval.

Conflict of Interest

There is no conflict interest.

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