Computational Fluid Dynamics Strategies for Detailed Transmission Loss Prediction in Silencers to Achieve Enhanced Performance

Abhijeet
M.Tech Scholar
Department of Mechanical Engineering
Millennium Institute of Technology
Bhopal, Madhya Pradesh, India

N.V. Saxena
Head of Department
Department of Mechanical Engineering
Millennium Institute of Technology
Bhopal, Madhya Pradesh, India
nishant.mgi@gmail.com

Abstract: Silencers are important noise control elements found in industries such as automotive, industrial machinery, HVAC, and aerospace for reducing unwanted noise and achieving operational efficiency. Transmission Loss (TL) describes one of the oldest parameters in the design considerations of a silencer and signifies the effectiveness of a silencer in sound attenuation. Predicting TL in complicated geometries using conventional methods is difficult, challenging, and time-consuming. Thus, the review examines the advanced computational techniques, particularly Computational Fluid Dynamics (CFD), as a potent simulation tool for modelling gas flow and acoustics in silencers. CFD allows designers to predict how sound propagates, absorbs, reflects, and how flow dynamic interacts with the silencer, followed by optimized designs without physical prototyping. It then also helps to cut down the number of design iterations required and minimize costs associated with physical testing to comply with noise regulations. The review further considers factors such as the influence of material properties, geometry, and flow dynamics in TL, while discussing also the challenges and opportunities for deploying CFD in enhancing the performance of silencers.

Keywords: Computational Fluid Dynamics (CFD), Transmission Loss (TL), Silencer Design, Noise Reduction, Acoustic Performance, Gas Flow Simulation, Multi-Physics Modelling, Flow Dynamics, Sound Propagation

I.INTRODUCTION

A silencer is a mechanical noise-control device used to reduce the noise made by a working system, making the silent surroundings unbearable to the ears, in the presence of blunt high-pressure gas or air flow. In essence, it's a mechanical noise-control device affecting any industry, varying from automotive exhaust systems to industrial machinery, HVAC technology, and much more, and even up to aerospace [1]. In essence, silencing mechanisms work by capturing sound energy and dissipating it by means of a host of mechanisms used to absorb, reflect, and scatter the sound, to lower its intensity before its waves travel and disturb the other surrounding area. In reducing the amplitude and frequency of noise output, silencers foster acoustic comfort in working environments, residential areas, and natural surroundings, paying due respect to local and global noise regulation compliance [2]. The relevance of silencers is more than just reduced noise; rather, these mechanisms are also directly participating in boosting health, fostering well-being, and reducing such detrimental effects of noise pollution that are related to some health concerns like hearing loss, stress, and disturbed sleep [3]. In the present-day world, where noise is of the greatest sensitivity, demand for advanced silencer designs with better noise control, efficiency, and less impact on the environment is fast increasing, and these are, therefore, an important area for the new advances in acoustics and mechanical engineering [4]. The figure 1 shows a muffler design with internal perforated tubes and baffles to reduce noise by dissipating sound waves through absorption and turbulence [5].

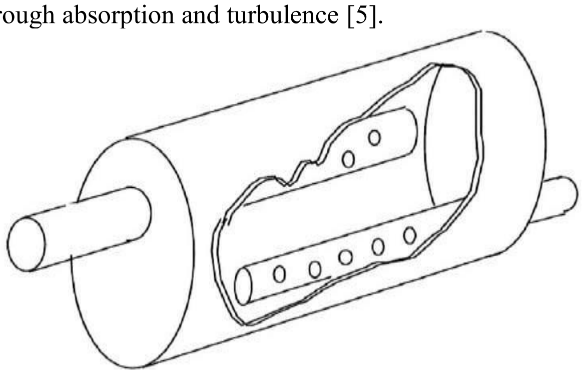

Figure 1 A reactive muffler with no direction connection between the inlet and outlet [5]

Transmission loss (TL) is the basic requirement for silencer design, which directly influences the worthiness of the device to the performance of noise attenuation. Simply put, it is defined as the amount of sound energy that is absorbed, reflected, or dissipated when sound waves pass through a silencer; the higher the transmission loss, the more noise is attenuated. High transmission loss is called for in the design of silencers to cope with the noise of engines, exhaust systems, or industrial machinery within the legal noise limits and create an acoustically friendly environment [6]. There are various influencing factors on the performance of a silencer; material selection, internal geometry, and sound wave energy dissipation methods such as absorption, reflection, or deflection. Besides, the gas flowing through the silencer and the incorporation of sound wave movements with the silencer structure have an influence on TL; that is, on the optimization of the design of the silencer, that would give all aspects well balanced - reduction in noise to keep the engine or machine working at the best performance while not emitting excess noise [7]. Nowadays, noise pollution is a growing problem worldwide, so the transmission loss achieved through silencer design can be considered the most crucial aspect against environmental and health impacts due to noise pollution. Hence, it is vital to consider transmission loss in the design and optimization process of a silencer to comply with regulations and further improve system performance [8].

The study of advanced computational techniques in prediction of transmission loss arises due to the increasing complex nature of modern silencer designs, along with a need for more accurate, efficient, and cost-effective noise reduction products. Classical experimental and analytical techniques have oftentimes been incapable of assimilating the transmission loss predictions for complex geometries, properties, and flow conditions [9]. These traditional techniques are often costly, time-consuming, and may neglect important variables as considerations. Advanced computational techniques in particular Computational Fluid Dynamics (CFD) are a good tool for simulating and predicting the acoustics and flow behaviour of silencers allowing designers to optimize designs much earlier before physical prototypes are manufactured [10]. In CFD, fluid dynamics get intertwined with acoustics, leading to an understanding of sound wave propagation, absorption, and reflection features occurring in a silencer, whereas, at the same level, flow velocity, turbulence, and material properties will exert their influence. This provides shorter iterative designs, reduced product development costs, and enables accurate predictions related to transmission losses, which ultimately provides bettering products and performance in silencer systems and compliance with regulatory noise standards [11]. The increasing demand for quieter and more efficient systems thereby emphasizes the importance of advanced computational techniques in predictions of transmission loss as a catalyst for innovation and a measure for noise control.

II.TRANSMISSION LOSS IN SILENCERS

Transmission loss (TL) indicates how well soundproofing or noise control devices (like silencers) attenuate sound as it travels through a material or structure. It is defined as the difference in sound pressure level between the sound entering and exiting a system, generally expressed in decibels (dB), and measures how much sound energy is absorbed, reflected, or otherwise dissipated by a material or structure, with higher TL indicating greater sound attenuation and better noise control [12]. It is critical in the silencer design process because the TL factor directly evaluates the ability to mitigate unwanted noise in cases involving automotive exhausts, industrial machinery, and HVAC equipment. In turn, TL depends upon numerous factors including the material (density and porosity), geometrical features of the silencer, frequency of sound, and flow characteristics of the medium (air or exhaust gases) [13]. The primary goal in a good silencer design is to enhance transmission loss in its operating frequency range for optimum sound attenuation without lowering the performance of the system in terms of airflow or engine. The more TL is understood and improved, the higher the level of competency contributed towards designing an efficient noise control solution, thereby earning TL a primary consideration in both the design and evaluation of silencers [14].

A. Factors Influencing Transmission Loss in Silencers

There are quite a few factors which affect TL in a silencer and among them, the most significant would-be material properties because that determines the overall efficiency of the silencer. Choosing materials indicates how the silencer absorbs sound will reflect or transmit noise and straightforwardly handle the gas or air flow. Materials with high density and porosity are good options for sound absorption, but smooth, non-porous surfaces reflect sound waves instead of absorbing them [15]. Yet, the thickness of the material also plays an important role, and generally, it is very likely that a thicker material increases sound insulation. In addition to that, the sound transmission can be affected by the temperature and pressure of the medium flowing through the silencer since sound travels differently in hot and cold or pressurized environments [16]. Another Incorporation is the geometrical design of a silencer. It consists of the shape, size, and internal configuration of the silencer-either presence of baffles, perforated tubes, and internal chambers; all these configurations play a direct role in the interaction of the sound wave propagation with the silencer [17]. Baffles help disrupt the flow of sound waves and create reflections that interfere with and cancel out certain frequencies; rather, perforated tubes, which promote sounding wave energy dissipation while enabling the flow of gases through small openings, more internal components keep acoustic impedance, and the way sound waves are refracted or absorbed by the interior design states a lot to the TL [18]. The frequency of the sound waves is also important: different silencer designs would generally be high or low efficient in damping different signal frequency ranges. Generally, low frequencies such as those produced by large engines or exhaust systems require large, complex silencer designs, but high-frequency noise may be handled easily by relatively straightforward internal designs. Flow dynamics, such as that of the velocity, turbulence, and pressure of gases passing through the silencer, may also enhance or degrade noise reduction [19]. While high-velocity flows often introduce additional turbulence that may raise noise, a well-optimized flow path can accomplish the opposite while improving the transmission loss. Thus, to enhance noise control across a wide range of applications, it is vital to understand the connection between these factors.

The material and acoustic-flow characteristics of a silencer unquestionably determine its potential to react efficiently to noise. Acoustic characteristics describe the phenomena concerning how sound waves behave when dispersing into or away from the silencer structure and internal reactants. The basic parameters for sound absorption, reflection, and dissipation by the silencer are the internal configuration of the silencer, the presence of baffles, perforated tubes, and the configuration of the sound-dampening or sound-scattering materials [20]. Flow characteristics are based on the flow of exhaust gases or given airs in the silencer proper. The sound waves are affected by velocity, pressure, and turbulence of the flow. For example, if flow velocity is increased excessively, noise and turbulence are created, scattering the performance of the silencer, whereas smoothly controlled flow brings about higher sound attenuation by silencer design. Material properties are also critically important [21]. Denser materials tend to achieve better soundproofing as they tend to reflect or absorb sound waves. Porous materials, on the other hand, tend to be excellent sound absorbers as they allow sound waves to get in and out through the structure of the material. Thickness also matters: the thicker the materials, the better they perform in attenuating sound, especially at lower frequencies [22]. In addition, viscoelastic materials that combine both elastic and damping properties will aid in sound absorption vibrations, thus increasing noise reduction. The gases' temperature and pressure flowing through the silencer would also impact the acoustic and flow characteristics since sound travels differently under hot or cold and high pressure or low-pressure conditions. The best combination of these factors-acoustic design, material properties, and flow dynamics-was used to infer how efficiently a silencer manages transmission loss of noise from the considered generation to maintaining the system efficiency [23].

III.COMPUTATIONAL FLUID DYNAMICS (CFD) IN SILENCER DESIGN

Computational Fluid Dynamics (CFD) is essential in silencer design, providing a modern and accurate tool to simulate and analyse the gas flow and sound waves in a silencer. CFD is a computational approach using algorithms and numerical methods to solve and analyse fluid flow, heat transfer, and acoustic interactions, giving engineers the capability to foresee the behaviour of exhaust gases or airflows and consequently predict their effects on noise attenuation. In combination with acoustics, CFD allows designers to model the complex interactions between the fluid dynamics and acoustic characteristics of the silencer's structure, including the influence of internal baffles, perforated tubes, or chambers upon sound-wave propagation [24]. It is also used to assess important flow characteristics such as turbulence, pressure drops, and velocity distributions, which significantly determine the silencer's efficiency in noise reduction. Additionally, CFD aids in the simulation of materials and geometries in further detail to optimize the design of the silencer even before any physical prototype construction-the testing stage that is commonly long and protracted [25]. Moreover, the use of CFD becomes crucial for perfecting silencer components by optimizing the internal features in relation to their location and size for maximum transmission loss and acoustical performance. With the ability to simulate real-life conditions and give precise predictions, CFD has turned out to be very useful in the design, supplying an insight into the work being done on silencers under varied operating conditions and helping engineers design more effective, efficient, and quieter silencer systems [26].

Computational Fluid Dynamics (CFD) applies numerical methods and algorithms to solve and analyse fluid flow, heat transfer, and associated physical phenomena. CFD uses the governing equations of fluid mechanics, namely, the Navier-Stokes equations that describe the motion of fluids in terms of velocity, pressure, density, and temperature. These equations are based upon the conservation of mass, momentum, etc., and are resolved over a computational grid which divides the physical space into smaller discrete elements [27]. First in order is the discretization of the problem, wherein the continuum mechanics domain is divided into smaller cells or elements, which is known as meshing. Boundary values and solutions are calculated for each cell in the meshed domain. For the purpose of the simulation, the governing equations are solved numerically using the finite volume method (FVM), finite element method (FEM), or similar approximation techniques [28]. The governing equations, discretization, and boundary conditions are imposed to simulate the real case scenario of inflow and outflow, wall interaction, etc. The steps of CFD indicate the velocity, pressure, turbulence, temperature distribution, fluid-solid interaction (example; fluid-structure interaction) are some of the important parameters that give a footing in the case for post-calculation insights [29]. In some applications, for instance, in the design of silencers, CFD includes acoustic modeling to predict how the sound waves interact with the fluid flow and with the silencer structure itself. This entire modeling helps the engineers to understand and optimize performance for different situations in complex systems, reducing the need for expensive and time-consuming physical prototypes. CFD provides the ability to visualize the pattern of flow, point out possible inefficiencies, and guide the engineer's decisions in making improvements in designs [30]. The fundamental equations in Computational Fluid Dynamics (CFD) are based on the conservation laws of mass, momentum, and energy. These equations describe how fluids behave under different conditions, and they are the core of CFD simulations. Below are the main governing equations used in CFD:

- **Continuity Equation (Conservation of Mass)**

The governing equation serves mass continuity in fluid flow. The governing equation is:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0$$

Where

ρ is the fluid density,

v is the velocity vector,

$\nabla \cdot$ represents the divergence operator (which calculates the rate of change of volume per unit of space),

t is time.

- **Navier-Stokes Equation (Conservation of Momentum)**

The Navier-Stokes equations describe the motion of viscous fluid substances, and these equations are rooted in Newton's second law of motion. In the case of incompressible Newtonian fluids, it states that:

$$\rho\left(\frac{\partial v}{\partial t} + v \cdot \nabla v\right) = -\nabla p + \mu \nabla^2 v + f$$

Where

p is the pressure filed,

μ is the dynamic filed,

∇^2 is the Laplacian operator (which represents the diffusion term),

f represents body forces (like gravity) acting on the fluid

This ordinant equation is essential in the various modelling of fluid flow behaviour, be it for turbulent or laminar flow.

A. Role of CFD in Noise Control and Transmission Loss Prediction

CFD plays an important role in the entire comprehensive noise control as well as prediction transmission losses that predict using modelling of flow associated with acoustics in silencer. Detailed simulation of gas or air flow through complex silencer geometries is ideal when having an accurate prediction of flow dynamics such as velocity, turbulence, and pressure distributions with respect to their effects on sound propagation and noise attenuation [31]. CFD allows the engineers to analyse how the sound waves propagate through the fluid and interact with the silencer's internal structures, such as baffles and perforated tubes in optimizing the acoustic performance. In addition, the contribution of CFD to optimization of silencer design has also been in understanding how a given change in the design, application of a geometry, material properties, or internal features will affect the transmission loss [32]. By simulating different conditions and configurations, CFD sees through to identifying the design that maximizes sound attenuation with low pressure losses while meeting efficiency in the system. The rapidity at which iterations could be made and predicted would outpace similar changes through conventional methods with a lessened reliance on expensive and time-consuming physical testing, resulting in silencers less than or more efficient, effective, and compliant with environmental standards [33].

B. Challenges in CFD for Silencer Design

One of the major challenges posed by computational fluid dynamics (CFD) importation in the design of silencers is that of complex geometries subsequent to the requirement of multi-physics simulation. It will also include complex internal structures like baffles, perforated tubes, and chambers as well as flow paths within a silencer, all of which can influence the flow dynamics significantly and their acoustic performance. Such complex geometries require a very highly meshed computational domain, increasing the amount of computational cost and time taken during the actual simulation [34]. Simultaneously, applications of CFD in silencer design need to consider several multiple physical phenomena at a time: fluid flow, heat transfer, turbulence, and acoustics. Such phenomena jointly complicate the simulations because they require advanced models and high computational power for accurate and effective solving of the governing equations. Simultaneously, a challenge is presented in terms of balancing the accuracy required with computational feasibility [35]. Thus, it becomes necessary to decide carefully the type of numerical methods to be applied and the type of meshing strategies.

Artificially intelligent machines are indeed having quite a significant role in everyday human life because they say that it has taken away human work by making it easier. Quite a few areas in general life make use of CFD, such as design and production, which include silencer design. Another major challenge in CFD for silencer design would be the accuracy and validation of the models [36]. The CFD simulations are very critical to the input parameters such as the properties of the material as well as the boundary conditions with flow characteristics. Even small discrepancies in these inputs produce a great variation in the results. Also, validating CFD models with respect to the real experimental data is very important for reliable predictions. However, validation will be made tough and a time-consuming process due to the complexity of these silencer systems and the challenges in choosing very precise experimental data. The result is that there is a chance that the simulation result does not represent the silencer performance in reality, which leads to inferior designs [37]. Thus, CFD has to be tied with experiment testing for cross-checking the outcome and improving the model so that the final silencer design is top-of-the-line concerning performance requirements in terms of noise reduction and operational efficiency.

IV.ADVANCED CFD STRATEGIES FOR TRANSMISSION LOSS PREDICTION

Advanced CFD strategies for predicting transmission loss include new numerical approaches in multi-physics simulations and improve transferability for very accurate and efficient designs. These advanced strategies are included in addition to fluid flow simulation and consist of components for acoustic modelling that predict sound transmission, sound incidence, and back current losses from the silencer structure. One example is hybrid CFD-acoustic methods [38]. On these lines, a model would be constructed by coupling fluid dynamics and acoustics, showing how a sound wave propagates through the perforated tubes, baffles, or other types of absorptive material present in the silencer interior and how it is attenuated as it impinges on those objects. Thereafter, multi-physics modelling is also significant to include fluid dynamics, heat transfer, and acoustic behaviour to complex interactions. Typically, these are for systems where high performance is required-the flow conditions and the thermal effects usually affect sound attenuation considerably [39]. Advanced turbulence models, for instance, LES or RANS, are used for considering the fine details of flow turbulence that have a direct impact on noise generation or indirect transmission loss. More often, optimization techniques go hand in hand with CFD simulation. Using genetic algorithms or gradient-based optimization using some algorithms, the design will be iterated to give the maximum transmission loss at performance with minimum pressure drop and structural constraints. With these generation advanced CFD strategies, it would have better predictions and minimize dependency with prototypes and would carry much profound information about design modifications on how they will affect noise reduction-related subjects, making it very important in the manufacturing of very efficient silencer systems [40].

Hybrid CFD-acoustic methods use the power of computational fluid dynamics (CFD) and other numerical techniques such as the Finite Element Method (FEM) and Computational Aeroacoustics (CAA), offering better prediction of transmission losses through silencers. While combining CFD with FEM for modelling both fluid dynamics and structural vibrations, flow in interaction with sound wave propagation becomes even more real with very complex silencer geometries [41]. Computational

Aeroacoustics (CAA) is utilized for simulation of high-frequency sound, essential for modelling turbine noise, for aerial and oceanic noise, and finally due to turbulence and flow instabilities in exhaust systems. It opens up paths for deeper analyses in sound attenuation and has implications in the design of silencers through an efficient and accurate prediction of noise reduction over a range of frequencies [42].

V.APPLICATIONS OF CFD IN SILENCER PERFORMANCE ENHANCEMENT

Automotive Silencers a very major application of CFD, indeed one of the most important, is in silencer performance improvement applications in the automotive industry where a reduction of engine noise while maintaining performance has become critical. CFD simulation addresses the modelling of exhaust gas flow and the evaluation of silencer-different designs relative to sound attenuation [43]. The process involves the simulation of the actual exhaust gases filter through the silencer's internal components such as baffles and perforated tubes and optimized geometry for noise reduction but not exhaust flow efficiency compromise. Prediction CFD can also be used very powerfully to assess how a variety of conditions such as flow velocity and turbulence can affect the silencer in the case of its attenuation of low-frequency engine noise [44]. This enables the design of silencers that would fulfil noise regulations without compromising vehicle performance, fuel economy, or durability.

Across industries and in HVAC systems, silencers serve as noise-dampening devices that lessen noise output from machinery, ducting systems, and air compressors. This technology is increasingly becoming an essential means of improving silencers' performance through accurate prediction of sound wave propagation through large, complex systems [45]. By modelling airflow and acoustic behaviour within silencers, CFD allows internal optimising features such as absorptive materials and the design of chambers to be configured for the required noise reduction over different frequency ranges. It is also possible to obtain a one-on-one balancing of energy loss by the silencer and its acoustics performance requirements for the industrial or commercial environment. All these aspects become very critical in environments where sound controls are necessary for the health, safety, comfort, and legal compliance of workers [46].

CFD plays an indispensable role in the design of silencers for application areas such as aerospace and marine sectors, where it is important to control engine and propulsion system noises. Jet engine silencers, turbomachinery silencers, and marine vessel silencers face unique challenges involving high-flow velocities, turbulent flows, and strict noise attenuation requirements [47]. Engineers can simulate high-speed flows and acoustic effects in silencer design using CFD such that the noise is reduced, while the performance of these systems is not compromised. In this way, noise-producing conditions such as those created by turbulent flow, engine operation, and exhaust gases can also be used to model both the fluid dynamics and the acoustic behaviours of such systems; thus, producing a silencer that provides high-frequency noise attenuation, improving overall acoustic performance and efficiency in the propulsion systems of aerospace and marine vehicles [48].

Treating the organization of the genome in three dimensions presents another epigenetic layer in gene expression. Active transcription, the indicative fruit of enhancers or super-enhancers, is by far most researched on. Activated transcription via enhancers or super-enhancers does recruit activators or co-activators to turn on target gene transcription through long-range chromatin interaction. There are also factors like chromatin interactions and phase separation, which are quite critical for enhancer or super-enhancer functioning. The other major types of cis-regulatory elements include silencers which directly activate a gene transcription, turn it off, or even reduce expression, although studies on silencers are still in an early stage compared to those of active transcription. It highlights the current understanding of human silencers, especially in their affinity for chromatin interactions and phase separation, besides assessing future directions for silencer studies [49].

For the transformer, openings for ventilation are required to enable noise to radiate outside; however, a modified design would include a soundproof window, which would achieve both air circulation and noise attenuation simultaneously, using a silencer with two coupled tubes that would provide attenuation at multiple frequencies for key frequency noise reduction [50]. Bioactive natural composite materials development includes polymer matrix composite from natural waste, particularly chicken feather fiber (CFF), and is applied in the manufacture of the eco-friendly prototype bike silencer with optimal mechanical properties and good noise reduction and absorption of pollutants coupled with heat release [51]. Generic applications of passive acoustic treatments to low-frequency noise, such as those of Helmholtz resonators in rectangular waveguides, were calculated as valid by simulations and measurements under relevant design optimization over the ventilation application [52]. Silencers also play an important role in immune regulation, as shown by the CNS-28 silencer within the Ifng locus that restrains IFN-γ production by immune cells to prevent autoimmune responses [53]. In marine engineering, a composite scrubber for ships would deplete sulphur oxide emissions without compromising noise. Vane type and resonate-type silencers were analyzed and compared for their noise reduction and pressure drop [54]. Splitter silencers, which are popular in systems such as ventilation and turbines, provide broadband attenuation of noise, and a new analytical method for predicting the propagation of sound in ducts of finite length gives accurate predictions not only of transmission loss but also of performance analysis [55]. The green synthesis of silver nanoparticles from Dioscorea cirrhosis tuber exhibits antimicrobial property which may be exploited further in bioactive materials, including silencer development [56]. In genome regulation, the silencer in the SMIM45 gene turns on the expression of divergent open reading frames but has implications for development in the brain and evolutionary gene regulation

[57]. It is proposed that the divergence of gene expression of paralogous nubbin/pdm2 genes in wing development in Drosophila melanogaster goes back to a pdm2-specific silencer; this silencer represses gene expression through one T.F. contributing to functional compensation when disturbed [58]. The ZNF382 protein silencer-mediated inhibition of Cxcl13 transcription in dorsal root ganglion neurons is implicated in the modulation of pain in neuropathic pain studies, further reinforcing the influence of silencers in gene expression epigenetic regulation related to pain responses [59].

Table 1 Comparative Analysis of Silencer Functions and Applications in Recent Studies

Reference	Study Focus	Key Findings	Methods	Outcomes
[49]	Human silencers, chromatin interactions, and phase separation	Roles of silencers in gene regulation and future research directions	Chromatin interactions, phase separation, and genetic analysis	Suggests further exploration of chromatin interactions in silencers
[50]	Transformer noise reduction with soundproof window and silencer design	Design that allows ventilation and noise attenuation at key frequencies	Silencer design for noise reduction and air circulation	Proposes practical solutions for noise reduction and air circulation
[51]	Bioactive natural composite materials for eco-friendly silencers	Natural composite materials for creating eco-friendly, efficient silencers	Natural waste fiber composites, mechanical testing	Developed hybrid composites for silencers with improved properties and eco-friendliness
[52]	Helmholtz resonator arrays for passive acoustic treatments	Optimization of Helmholtz resonators for noise reduction performance	Helmholtz resonator arrays, optimization through transfer matrix method	Provides optimized passive design for noise reduction in waveguides
[53]	CNS-28 silencer in immune regulation, IFN-γ expression	CNS-28 silencer modulates immune responses by restraining IFN-γ expression	Chromatin silencing, GATA3 and T-bet regulation	Highlights CNS-28 as a key element in regulating immune responses and autoimmunity
[54]	Composite scrubbers for ship exhaust and noise reduction	Composite scrubbers reduce sulphur oxide and exhaust noise simultaneously	Vane-type and resonate-type silencers, pressure drop analysis	Offers a practical solution for reducing both sulphur emissions and noise on ship
[55]	Splitter silencers for broadband noise attenuation in ducts	Analytical approach for predicting splitter silencer performance in noise attenuation	Splitter silencer analysis, dissipation vs. reflection	Introduces an analytical method for predicting splitter silencer noise attenuation
[56]	Green synthesis of silver nanoparticles for antimicrobial properties	Antimicrobial properties of silver	Green synthesis of silver nanoparticles,	Demonstrates the potential of green synthesized

		nanoparticles synthesized from Dioscorea cirrhosa tuber	antimicrobial testing	nanoparticles in bioactive applications
[57]	SMIM45 gene regulation with silencer and evolutionary significance	Regulation of SMIM45 ORFs by a silencer, evolutionary development insights	Genetic regulation of SMIM45 and evolutionary analysis	Explains how a silencer regulates SMIM45 gene expression with evolutionary relevance
[58]	Gene expression divergence in Drosophila with silencer role	Functional divergence of nubbin/pdm2 genes in Drosophila with silencer mediation	Gene expression analysis of paralogous genes in Drosophila wings	Clarifies gene expression divergence through silencer involvement in development
[59]	Neuropathic pain and silencer-mediated gene regulation in DRG neurons	Silencer-mediated Cxcl13 transcription regulation in neuropathic pain modulation	ZNF382 silencer-mediated transcriptional regulation in neuropathic pain	Explores the role of silencers in neuropathic pain regulation and gene expression

CONCLUSION

Advanced computational methods, and especially CFD, have become indispensable tools in the design and optimization of silencers. Fluid dynamics and acoustics combined in CFD simulate sound waves and gas flows in complicated silencer geometries, making it much more accurate in predicting transmission loss. This method hastens the design procedure and thereby eliminates expensive and time-consuming physical testing. A plethora of problems and challenges such as the extremely complicated nature of modeling multi-physics interactions and the lack of experimental data needed to validate CFD models, however, do not prevent the beat of CFD innovation in silencer technology. Adding CFD support to materials science, structural optimization, and advanced turbulence models is likely to offer solutions for achieving potentially higher levels of noise reduction without compromising efficiency. With industries emphasizing noise reduction and green concerns day by day, CFD's role in silencer design would eventually become more significant in delivering quieter, yet efficient systems, while complying with global noise regulations.

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