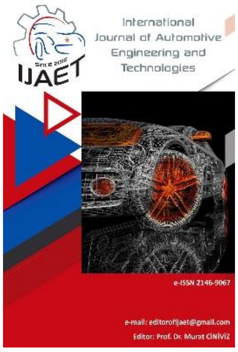
e-ISSN: 2146 - 9067

International Journal of Automotive Engineering and Technologies

journal homepage:
https://dergipark.org.tr/en/pub/ijaet



Original Research Article

Numerical investigation of the thermal and acoustic effect of material variations on the exhaust muffler

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ARTICLE INFO

Orcid Numbers

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Doi: 10.18245/ijaet.1407245

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Received: Dec 20, 2023
Accepted: Mar 11, 2024

Published: 27 Mar 2024

Published by Editorial Board Members of IJAET

ABSTRACT

Exhaust mufflers are used in automobiles to prevent the noise arising from exhaust gases resulting from internal combustion engines. With the advancement of the automotive industry, exhaust mufflers have become more complex over time to reduce noise and increase driving comfort. Within the scope of this study, exhaust muffler geometries with different geometries have been designed, and harmonic acoustic analyses have been carried out. In the analysis, the airflow speed has been accepted as 30 m/s. Acoustic pressure and transmission loss data obtained because of analyses performed with 1Pa pressure input have been evaluated. As a result of the evaluations, it has been concluded that the muffler modeled in a complex structure has been better acoustically. Although the main task of exhaust muffler is to reduce the sound level at the exit of exhaust gases, it is also important to reduce the temperature of the air in the exhaust system and have good thermal conductivity so as not to jeopardize the thermal safety of the system. For this reason, CFD thermal flow analysis has been carried out with 4 different materials using a complex design with high acoustic efficiency. Gray cast iron, stainless steel, 1020 steel, and aluminum have been used as materials. In this part of the study, it has been determined that the use of aluminum material has been better in terms of thermal efficiency.

Keywords: Exhaust muffler, Harmonic acoustic analysis, Thermal flow analysis, Computational fluid dynamics.

1. Introduction

The automotive exhaust system controls and directs the exhaust gases resulting from engine combustion. It also helps minimize environmental impact by reducing emissions. The exhaust system usually includes components such as the exhaust manifold, catalytic converter, exhaust pipe, and exhaust muffler. The exhaust manifold collects exhaust gases from the engine's cylinders and directs them to the catalytic converter. The exhaust pipe connects to the exhaust muffler as it carries the exhaust gases out of the vehicle [1]. In the early periods of the automobile industry, the control of exhaust gases resulting from internal combustion engines was not given much importance. During this period, exhaust gases were released directly from the vehicle into the atmosphere. Exhaust systems consisted of a simple pipe structure and generally provided no emission control. The 1960s and 1970s were the periods when emission control in exhaust systems gained importance. With increasing environmental concerns, the need to reduce emissions of exhaust gases has emerged. Since the 1980s, emission control in exhaust systems has been further developed. More advanced technologies and systems have begun to be used to reduce harmful components in exhaust gases. Emissions have been further reduced with innovations such as fuel injection, exhaust gas recirculation systems, and more efficient catalysts. Additionally, sound control in exhaust systems has also gained importance. Exhaust mufflers are a type of acoustic filter used to reduce exhaust sound. The basic structure of this component includes perforated channels, partitions, and expansion chambers. Exhaust mufflers have become more sophisticated day by day to reduce noise and increase driving comfort. Exhaust mufflers, which contain sound-absorbing materials and resonators, have become capable of preventing unwanted noise by absorbing sound waves [2,3].

Today, exhaust systems used in automobiles have become more advanced and effective in terms of emission control and sound control. New technologies and regulations make exhaust systems more environmentally friendly and high-performance. The exhaust muffler is an important component of the exhaust system and reduces the noise generated by the engine. Exhaust muffler designs have undergone significant changes over time. While it initially had a simple structure, more complex and effective designs were developed in the following years. Additionally, advances in material technologies have enabled the use of lighter and more durable materials. This increased the performance of exhaust mufflers and ensured their longevity. Over time, the designs and functions of exhaust mufflers have improved. While simple sound-absorbing materials were used in the early periods, today more complex structures and acoustic principles are used. Additionally, the sizes and shapes of exhaust mufflers have varied depending on the performance requirements and design preferences of vehicles [4]. In addition to design, the materials used for muffler performance are also very important. The most used material in the production of exhaust muffler is steel. Especially stainless steel is preferred due to its durability and corrosion resistance. Steel is a material with high-temperature resistance that is resistant to the high temperatures of exhaust gases. Due to its lightness, aluminum is a preferred material in the production of exhaust mufflers. After the 2000s, fiberglass began to be used as a sound-absorbing material inside the exhaust muffler. Nowadays, ceramic materials are also used in exhaust mufflers due to their high-temperature resistance and sound insulation properties [2,5]. Various performance tests are carried out to determine the performance and safety of mufflers. The most important of these are harmonic acoustic analyses performed to determine the acoustic performance of the system. With harmonic acoustic analysis, properties of the design such as acoustic pressure, transmission loss, and absorption coefficient under certain boundary conditions can be obtained numerically. As a result of the data obtained, various evaluations and optimizations can be made in the design [2].

In addition to harmonic acoustic analyses, flow analyses can also be performed to evaluate the flow distribution and thermal efficiency of exhaust mufflers. Flow analyses are important to evaluate the performance and optimized design of the exhaust muffler. Flow analysis is used to understand how exhaust gases move within the muffler and to examine the thermal efficiency of the material used in production [6]. These analyses evaluate parameters such as flow rate, pressure drop, orientation, and distribution of gases. The most used method in these evaluations is CFD.

There are many studies in the literature on this subject using the CFD method. Das and his colleagues designed a baffle plate to reduce the acoustic noise in automobile exhausts integrated it into the exhaust muffler and obtained a new design. They also compared the results obtained in their studies using numerical methods with experimental data. As a result, they found that the noise of the exhaust mufflers decreased with the use of baffle plates [7]. Kalita and Singh used different sound absorption materials such as glass wool, rock wool, and melamine to evaluate the acoustic performance of the hybrid exhaust muffler. They measured the pressure level in their studies using the CFD method. They found that the best acoustic material for automobile exhaust muffler is glass wool. They observed the same result again with the experimental setup they established [8]. Kalita and Singh determined four different models and performed acoustic analysis to optimize the exhaust muffler used in a 6000 RPM four-cylinder engine. The first model is designed with three chambers and a perforated tube, the second model with double chambers and a non-perforated tube, the third model with double chambers and a perforated tube, and the fourth model with double chambers and a double non-perforated tube. They analyzed the drawings they made using the CAD program using the CFD method. In the numerical calculations made, 80 m/s was selected as the fluid inlet speed. As a result, they found that the best acoustic performance was obtained from the fourth model. They found that the sound pressure level in the first model was around 75-78 dB, and in the fourth model, this level was around 45-50 dB [9]. Shi and his colleagues made a new design using metal foam material for acoustic insulation in automobile mufflers. They obtained the data in their study by using the CFD program and conducting experimental studies. As a result, they found that the metal foam exhaust muffler provides better heat dissipation, reduces the exhaust pressure by 8.4%, and reduces the noise by 44.4% [10]. Kashikar and his friends introduced a new design by optimizing the KTM 390 stock exhaust muffler to reduce exhaust noise. During their studies using the CFD program, they examined the torque curve, transmission loss, pressure change, and noise emission. According to the data they obtained because of their analysis, they produced and used the exhaust muffler they designed for the Formula Student race car [11].

Within the scope of this study, two different exhaust muffler geometries with different internal designs have been designed, and harmonic acoustic analyses have been carried out. By comparing the acoustic data obtained because of the analysis, where the airflow speed has been assumed to be 30 m/s, a design that produced less noise has been determined. Subsequently, CFD thermal flow analyses have been performed with four different materials using a design that produces less noise. The materials used in the study are gray cast iron, stainless steel, 1020 steel, and aluminum. Considering the thermal efficiency in exhaust mufflers, it has been determined that the use of aluminum material is better than others.

2. Material and Methods

2.1. Muffler Design

The exhaust muffler geometries used in this study have been designed in two different configurations using SolidWorks. Before modeling, a technical drawing has been made, free of details that would not affect the main outputs of the study. The reason for this is to gain speed in the design and analysis stages and then purify the analysis outputs from details that do not fit the essence of the study. In the initial design, a basic exhaust muffler model has been created. In the second design, a new channel with an additional curved structure has been added to the air inlet area on the exhaust muffler. The air ducts in the internal structure of the exhaust muffler have an important effect in terms of carrying and absorbing sound. While these channels regulate the flow of exhaust gases, they also affect the propagation paths of sound waves.

The air ducts in the internal structure create acoustic wave paths that are effective on the transmission of sound. The shape, size, and placement of these channels determine how sound waves of different frequencies travel. For example, with the right design, air ducts can increase the effectiveness of the exhaust muffler by absorbing sound waves at unwanted frequencies. This method has been preferred to examine the effect of an additional channel on absorption. Another detail in configuration number two is the number and size of holes in the muffler. The holes opened into the channels in the internal structure significantly affect the flow and sound absorption. The size, number, and placement of these holes affect the behavior of both flow and sound. The effect of the holes on the flow allows the exhaust gases to pass between the channels and affects the direction of the flow. The location and size of the holes can affect the flow rate and pressure drop. Larger holes allow more airflow, while smaller holes allow for higher velocity flow. Strategic placement of vents can ensure uniformity of flow and help distribute exhaust gases properly. The holes allow sound waves to enter the internal structure and be absorbed by the absorption materials inside. Larger holes allow more sound to enter and interact with the absorption materials. The dimensions of the designed exhaust muffler are as follows; shell length is 32.0", overall length is 36.25", inlet length is 2.0", body diameter is 8.3x11.5", inlet inner diameter is 3.5", and outlet outer diameter is 4.0". Technical and cross-sectional views of the created exhaust muffler designs are given in Figure 1 and Figure 2, respectively.

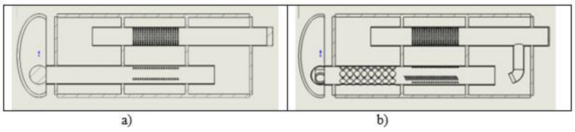


Figure 1. Technical views of exhaust mufflers; a) Simple design, b) Complex design

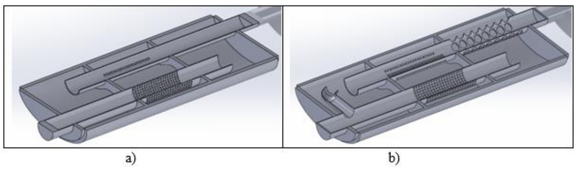


Figure 2. Sectional views of the exhaust mufflers; a) Simple design, b) Complex design

Many exhaust muffler designs and production are possible in today's automotive industry. As a result of the improvement of production technologies and their integration into the industry, many optimization options have emerged in exhaust muffler design. The design designed and analyzed throughout the paper is extremely suitable in terms of manufacturability and very useful in terms of performance. So much so that today's manufacturers use muffler designs with double outlets and perforated layers in the internal structure of many of their cars.

2.2. Meshing

Hexagonal and triangular elements have been preferred when creating the mesh structures of the exhaust muffler models. As a result of the meshing process, a network structure consisting of approximately 800,000 grids has been obtained. The created mesh structure is given in Figure 3.

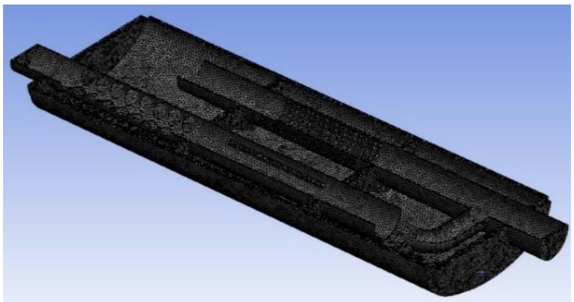


Figure 3. Mesh structure of the exhaust muffler

Getting a good result from finite element analysis is directly related to the precision of the mesh structure. For this, mesh independence work must be done. Getting a good result from finite element analysis is directly related to the precision of the mesh structure. For this, mesh independence work must be done. Factors that determine the solution quality of the finite element method are the sizes, widths, and y+ values of the mesh cells. In any CFD study, ideal element quality values should be higher than the average value of 0.8 as much as possible and should be close to the value of 1.00 [12]. The element quality of the mesh structure created within the scope of this study is very close to 1 on average. This shows that the mesh quality is suitable for analysis. Element skew rates are an important issue affecting quality. The skewness ratio in mesh structures is used to determine how close to ideal the elements can be modeled [12].

Skewness is a parameter that measures the geometric irregularities of a mesh file and is generally desired to have values close to zero. Lower skewness values indicate that the elements are better aligned without irregularities, which allows more accurate results from the analysis [13]. The Skewness value is used as an indicator expressing the geometric irregularities of the elements and usually takes a value between 0 and 1. The lower the Skewness value is the higher quality the mesh file [14]. The skewness range values of the created grids are given in Table 1.

Table 1. Distribution of the number of elements according to the skewness value

Skewness Range	Number of Elements	Percent
0-0.1	653360	80.22
0.1-0.2	121111	14.87
0.2-0.3	27773	3.41
0.3-0.4	12217	1.5
0.4-0.5	4812	0
0.5-0.6	0	0
0.6-0.7	0	0
0.7-0.8	0	0
0.8-0.9	0	0
09.-1	0	0

When Table 1 is examined, it is seen that 95% of the grids of the mesh file created for the exhaust muffler model have a skewness rate between 0 and 0.2. This shows that the mesh quality is quite good.

Upon the completion of the mesh file generation for this investigation, a meticulous evaluation of orthogonal alignment has been conducted to validate its integrity. The term orthogonal quality pertains to the geometric precision and fluidity among the elements within the mesh network. A heightened orthogonal quality denotes a superior alignment of elements, resulting in a more seamless interconnection [15]. This, in turn, establishes a foundation for more exact and dependable analytical outcomes. In the realm of finite element analysis, the significance of orthogonal quality arises from the fact that a subpar mesh network can precipitate inaccurate findings and flawed prognostications. To elucidate, a mesh network characterized by low orthogonal quality may disregard or misrepresent pivotal details such as stress concentration or load distribution. Proximity to the value of 1 in maximum values signifies a superior orthogonal quality, indicative of elements interconnecting at approximately 90-degree angles [16]. This proximity to unity is a coveted attribute for precision in results, underscoring the importance of well-connected element surfaces. The orthogonal quality range values of the created grids are given in Table 2.

When Table 2 is examined, the orthogonal quality range of the grids of the mesh file created for the muffler model is at an acceptable level.

Table 2. Distribution of the number of elements according to the orthogonal quality value

Orthogonal Quality Range	Number of Elements	Percent
0-0.1	0	0
0.1-0.2	0	0
0.2-0.3	0	0
0.3-0.4	0	0
0.4-0.5	0	0
0.5-0.6	547	0
0.6-0.7	170788	20.84
0.7-0.8	220134	26.86
0.8-0.9	245192	29.92
09.-1	182612	22.28

2.3. Materials

Four different materials have been used in the thermal flow analysis of the exhaust muffler models using the CFD method. These materials have been selected as gray cast iron, stainless steel, 1020 steel, and aluminum. These materials have been chosen because they are widely used in the market. Gray cast iron is an iron-carbon alloy composed primarily of iron, carbon, and silicon. It is widely used in casting processes due to its high-pressure resistance. It is preferred in components in the automotive industry such as exhaust mufflers due to its sound and vibration absorption properties [25].

Stainless steel is an alloy that contains elements such as iron, carbon, and chromium, and sometimes includes nickel and molybdenum. The chromium content provides corrosion and rust resistance to stainless steel. Stainless steel is also a frequently used material in the construction of exhaust mufflers. It is a preferred option in exhaust systems due to its high durability, corrosion resistance, and high-temperature resistance. Stainless steel exhaust mufflers can work effectively to reduce sound and absorb vibration [2]. 1020 steel belongs to the low-carbon steel class and contains elements such as iron, carbon, manganese, and sulfur. Thanks to its high strength and durability, it can be a suitable option for exhaust mufflers. 1020 steel stands out with its ability to absorb vibrations and reduce sound occurring within the exhaust system. In addition, the machinability and low cost of steel make it preferred in the production of exhaust muffler systems [26]. Aluminum is a material frequently used in exhaust muffler systems. Its lightweight, high strength, good thermal conductivity, and corrosion resistance make aluminum an ideal choice for exhaust mufflers. Aluminum exhaust mufflers reduce vehicle weight and increase fuel efficiency while providing durable and long-lasting performance [23]. In addition, the thermal properties of aluminum allow for more efficient heating and cooling by dissipating heat quickly. Its easy formability and machinability facilitate the production process and provide design flexibility. Some physical properties of the materials used in this paper are given in Table 3.

Table 3. Material properties [20]

Properties	Grey Cast Iron	Stainless Steel	Steel 1020	Al
Density, kg/m^3	7100	7750	7870	2700
Young's Modulus (Gpa)	125	190	190	69
Possşon's Ratio	0.25	0.3	0.29	0.34
Thermal Conductivity, W/mK	54.5	26	52	210
Specific Heat, J/kgK	586	500	470	900
Latent Heat of Fusion, kJ/kg	270	260	250	384
Thermal Expansion, 10^{-6}/K	11	9	11.7	22.2

2.4. CFD Analysis

In this study, two different numerical calculations have been made: acoustic analysis and thermal analysis. The harmonic theory of acoustic analysis is a field that studies how sound propagates after it has emitted from a source and how it behaves in various environments. This theory tries to explain acoustic phenomena such as sound propagation, reverberation, absorption, and echo times by analyzing the properties of sound waves such as frequency, amplitude, and phase [25]. The theory of harmonic acoustic analysis is a method used to analyze the properties of sound and predict the behavior of sound using mathematical representations of sound waves. Harmonic acoustic analysis theory divides sound waves into different frequency components and calculates the amplitude of each component.

Finite Element Analysis and Harmonic Acoustic Analysis are approaches used together in the analysis of sound and vibration problems. Although the two methods have different perspectives, they can be used together to solve sound problems. Finite Element Analysis is a method that divides a system into interconnected subsystems and analyzes the energy transfer of these subsystems in frequency ranges. FEA considers factors such as energy transfer, resonance frequencies, and energy dissipation. Combining harmonic acoustic analysis and finite element analysis provides an overall assessment of the acoustic performance of systems. Finite element analysis divides the system into subsystems and analyzes the energy transfer of these subsystems, while harmonic acoustic analysis evaluates the harmonic components and frequency response of the system. When these two methods are used together, a more comprehensive analysis of sound and vibration problems can be performed and provide guidance for improvements in the design process [18,19]. Harmonic acoustic analysis aims to determine the frequency components of the sound by analyzing the harmonic components of the system. This analysis is used to understand how the system behaves at certain frequencies. This theory of analysis evaluates the harmonic components of the sound, frequency response, amplitudes, and harmonic distortions. Harmonic acoustic analyses have a wide range of uses, from sound engineering to industrial product design to environments with state-of-the-art audio systems. Harmonic acoustic analysis, which is also widely used in the automotive industry, is frequently used especially in exhaust muffler designs. Noise levels of exhaust systems are evaluated by harmonic acoustic analysis. This analysis is used in the design of exhaust mufflers and resonators. Harmonic vibrations and sound waves caused by gas flow in exhaust systems are examined. This information is used to optimize the acoustic performance of exhaust muffler and reduce unwanted noise. Harmonic acoustic analysis is also used in vibration analysis of exhaust system components [24].

Exhaust systems are subject to vibrations due to gas flow and engine vibrations passing through them. Harmonic acoustic analysis is used to determine the vibration modes and frequency responses of exhaust system components. This information guides design changes used to optimize the durability and performance of components. The acoustic performance of the materials used in exhaust muffler is also evaluated by harmonic acoustic analysis. In harmonic analysis, a harmonic oscillatory force or vibration is applied to the system under study. This occurs at a frequency close to the natural frequencies of the system. Under the influence of a harmonic force, the system resonates and can produce large vibrations at certain frequencies. This method of analysis is widely used in solving vibration problems and acoustic propagation problems. This method uses a combined model between structuralist and acoustic analysis. In the first step, the mechanical behavior of the structure is examined, and its natural frequencies and mode shapes are determined. This mechanical model is then used to calculate sound waves propagating in the acoustic environment [25].

The design of automotive exhaust mufflers plays a pivotal role in influencing the performance, sound characteristics, and emissions of a vehicle's exhaust system. Acoustic analyses stand out as indispensable tools employed to attain the desired auditory experience, mitigate noise, and optimize the overall functioning of the engine [26].

Harmonic acoustic analysis deviates from other forms of acoustic analysis by concentrating on a distinct aspect. In contrast to the general evaluation of the entire sound spectrum or frequency distribution, harmonic acoustic analysis meticulously scrutinizes the specific harmonic constituents emitted by the exhaust system. These harmonic components represent regularly recurring frequency elements linked to the operational principles governing the engine and gas flow [27].

Automotive manufacturers are dedicated to upholding the targeted level of auditory excellence in their vehicles. Harmonic acoustic analysis empowers designers to enact modifications to the design by scrutinizing the specific harmonic constituents emitted from the exhaust system, ensuring the vehicle produces a pleasing and well-balanced acoustic profile [28].

The exhaust system serves as a pivotal element in diminishing the noise generated by the vehicle. Harmonic acoustic analysis proves instrumental in identifying optimal designs geared toward noise reduction, grounded in the operational principles of the engine and exhaust constituents.

Moreover, the exhaust system significantly influences engine performance. Harmonic acoustic analysis facilitates the assessment of the impact of harmonic constituents emitted by the exhaust system on the overall performance of the engine. This analytical approach aids in comprehending the repercussions of design alterations in the exhaust system on critical factors such as engine power, torque, and emissions. Consequently, judicious design modifications can be implemented to achieve heightened performance and diminished emission levels [29].

In this study, the frequency range is defined as a minimum of 0 Hz and a maximum of 3000 Hz. 3000 frequency values have been divided into 100 different ranges. The temperature of the air included in the inlet in the internal structure of the exhaust muffler has been determined as 30 m/s in accordance with academic and sectoral-based studies. In addition, the exhaust muffler pressure value is defined as 1Pa in accordance with the analysis conditions and design parameters. In any CFD analysis, another parameter as important as geometry design, mesh process, and turbulence method selection is determining boundary conditions. In this study, k-ε Realizable has been used as the turbulence method.

The k-ε turbulence model, the most widely used turbulence model, provides improved predictions of the propagation velocity of both planar and curved structures. It also provides very good performance under strong back pressure gradients. For this reason, k-ε realizable has been chosen as the most suitable model for exhaust muffler geometries.

This model doesn't well perform in cases of large adverse pressure gradients. It is a two-equation model, which includes two extra transport equations to represent the turbulent properties of the flow. This allows a two-equation model to account for historical effects like convection and diffusion of turbulent energy. The first transported variable is turbulent kinetic energy, k. The second transported variable, in this case, is the turbulent dissipation, ε. It is the variable that determines the scale of the turbulence, whereas the first variable, k, determine the energy in the turbulence [30].

For turbulent kinetic Energy, k;

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right]+2\mu_t E_{ij}E_{ij} - \rho\varepsilon$$

For dissipation, ε;

$$\frac{\partial(\rho \varepsilon)}{\partial t}+\frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij}E_{ij} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

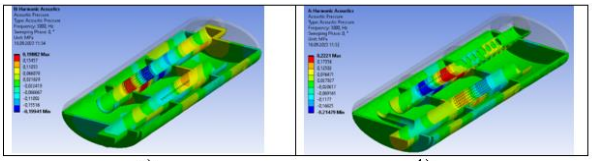
u_i is represents the velocity component in the corresponding direction, E_{ij} is represents a component of the rate of deformation, and μ_t is represents eddy viscosity [30].

In the analyses carried out within the scope of this study, air at 25 °C has been used as the fluid. Considering that the other parameters of the fluid are ρ=1.225 kg/m^3, μ=1.81x10^{-5} kg/(m.s) and the fluid speed v=30 m/s, the calculated Re value has been obtained as 3.1x10^6. This Re value obtained shows that the flow is turbulent.

3. Results and Discussion

3.1. Acoustic analysis

Acoustic pressure values obtained because of harmonic acoustic analysis express how much sound an element of a model produces at a frequency or how much sound it responds to. Acoustic pressure is the pressure changes created by sound waves at a point. In harmonic acoustic analysis, the analyzed model is exposed to vibrations or sounds, and the resulting sound pressure levels are measured. Harmonic acoustic analysis of the exhaust system can be used to determine sound pressure levels resulting from the exhaust system. It provides useful information in the design of measures such as noise control, vibration reduction, or sound insulation. The acoustic pressure value is also important to understand the effect of sound on people or other systems in the environment [24]. The data obtained because of the harmonic analyses performed according to two different configurations are given in Figure 4.



a) b)

Figure 4. Acoustic pressure results of exhaust muffler models; a) Simple model, b) Complex model

When the data obtained has been compared, it has been seen that the acoustic value obtained from the simply designed configuration with fewer air ducts and fewer holes has been higher than the complexly designed configuration. The maximum pressure value, measured as 0.2221 MPa in the simple design, has been recorded as 0.19882 MPa in the complex design. In this case, the complex design has been found to be more efficient in reducing noise production. Acoustic pressure values obtained for exhaust muffler designs express the sound reduction performance of the exhaust muffler. These values determine how the sound originating from the exhaust system is reduced within the muffler and the sound level emitted around the exhaust system. Low acoustic pressure levels indicate that the sound from the exhaust system is effectively reduced. This reduces the noise emitted into the environment during the operation of vehicles or equipment. Lower sound levels increase user comfort and reduce negative impacts on the environment. Low acoustic pressure values in exhaust muffler designs minimize performance losses due to the exhaust system. High-pressure loss can obstruct the flow of exhaust gases and adversely affect the engine performance. Therefore, it is important to aim for low-pressure loss while also providing effective sound attenuation.

Another measurement used during acoustic analysis is the transmission loss value. Transmission Loss is a measure of how a structure or material element reduces or blocks sound energy from a sound source. Conduction loss is usually expressed in certain frequency ranges and represents the energy loss of sound during its transition from one medium to another [25].

Transmission loss is usually expressed in decibels (dB). A positive transmission loss value indicates that sound energy is reduced, meaning less sound is passing through. A negative transmission loss value means that sound energy is increasing or more sound is passing through. A higher transmission loss means more energy loss and better sound insulation. Transmission loss is important for evaluating the effectiveness of the obstacles that sound encounters when passing from one medium to another. Transmission loss is used to evaluate sound insulation performance, to reduce sound transmission, or to control unwanted sound in a particular environment. This information is used in the design of structures requiring sound insulation or to help take appropriate measures for noise control in a particular environment. Transmission loss data obtained from two different geometries used within the scope of this study are comparatively given in Table 4.

Table 4. Transmission loss

	Simple model	**Complex model**
Hz	**dB**	
30	0	0
120	0	1.6935
150	0.9659	3.1594
1080	34.886	46.585
1200	21.345	9.3637
1500	14.966	19.238
1680	11.583	52.286
2130	26.706	28.058
2700	21.805	10.203
3000	25.142	19.293

When the transmission loss data of two different designs were examined, it has been seen that higher decibel values have been achieved in the complex designed exhaust muffler configuration and therefore higher sound absorption has been achieved. When the data obtained was evaluated, it has been thought that the main task of the exhaust muffler was to minimize the noise level. After it was decided that the model with complex geometry has been more efficient.

3.2. Thermal analysis

Although the main task of exhaust muffler is to reduce the sound level at the exit of exhaust gases, it is also important to reduce the temperature of the air in the exhaust system and have good thermal conductivity so as not to jeopardize the thermal safety of the system [31]. Exhaust gases have high temperatures resulting from engine combustion and as a result, they carry heat energy as they pass through the exhaust system. This heat can damage other components of the exhaust system or negatively affect fuel efficiency. Therefore, exhaust mufflers must have good thermal conductivity. In other words, while passing through the exhaust gases, the heat must be transferred to the outer surface of the muffler and radiate to the environment from there. This ensures thermal safety by cooling the exhaust system. The thermal conductivity of the exhaust muffler is related to the materials used and design details. Generally, exhaust mufflers are coated with materials that conduct heat better or have layers that provide thermal conductivity. In this way, the heat resulting from the exhaust gases is distributed more effectively from the muffler surface. For the two configurations for which harmonic acoustic analysis has been performed, configuration number two, which was designed with a complex structure, has been preferred for thermal analysis in this part of the study, as it was understood that the complex one has been a more efficient design in terms of acoustic pressure and transmission loss. In this part of the study, gray cast iron, stainless steel, carbon steel, and aluminum materials, which are frequently used by manufacturers in the manufacture of exhaust mufflers in today's automotive industry, have been identified and four different thermal flow analyses have been carried out. Contour views and graphs of the results obtained from the analyses are given in Figure 5 and Figure 6, respectively.

4. Conclusions

In this study, two different models have been designed to examine the effect of exhaust muffler internal structure geometries on acoustic pressure and sound absorption. Numerical analyses have been performed using the CFD method on the models drawn in the CAD program. The results obtained from these analyses have been interpreted comparatively.

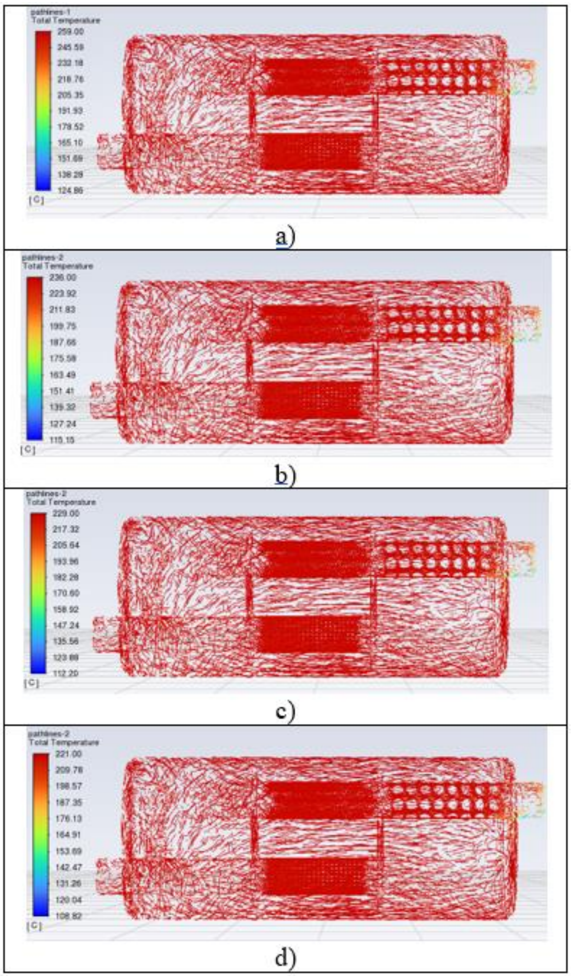


Figure 5. Thermal flow distributions; a) Gray cast iron, b) Stainless steel, c) Carbon steel, d) Aluminum

While the harmonic acoustic approach was chosen for the sound level calculations used in the study, k-e Realizable has been preferred as the turbulence model. Under the boundary conditions defined because of acoustic investigations, the maximum value of acoustic pressure obtained for a simple design is measured as 0.2221 MPa, while this value is 0.19882 MPa for an exhaust muffler with a complex structure. In the transmission loss results under the same boundary conditions, the maximum absorbed sound decibel for the simple design has been 34.886, while this value has been recorded as 52.286 dB for the complex structure exhaust muffler. In this case, considering both acoustic pressure and transmission loss data, it has been determined that the complex exhaust muffler design is more efficient in not spreading noise. When the two models were compared, it has been seen that the acoustic pressure value of the complex exhaust muffler was 10.48% lower than the simple one. This rate has been calculated as 33.28% in absorbed sound decibels. In a similar study conducted by Mohamed et.al in the literature, it was observed that the acoustic pressure decreased by 10% in the model designed by increasing the number of holes in the exhaust muffler [32]. It can be said that this value is like the results obtained in this study. In a similar study conducted by Ibitoye et.al in the literature, it was observed that the absorbed sound value decreased by 30% in the model designed by increasing the number of holes in the exhaust muffler [33]. It was found to be like the results of the analyses conducted within the scope of this study.

After it has been observed that the exhaust muffler designed with a complex structure was more acoustically efficient, thermal flow analyses have been carried out on the complex structure design to compare the thermal efficiencies of four different materials. According to the data obtained, aluminum has been seen as the exhaust muffler material with the best thermal properties, with a maximum temperature value of 221°C. This value is 229°C for 1020 carbon steel, 236°C for stainless steel and 259°C for gray cast iron. It has been observed that when aluminum was used instead of gray cast iron as the exhaust muffler material, the surface temperature would be 14.68% lower. This value is 6.36% for stainless steel and 3.89% for 1020 carbon steel. As a result, aluminum has been the recommended material to minimize thermal problems. It has been determined that the use of aluminum, which is the material with the lowest temperature value, would be more accurate than others.

Acknowledgment

Appreciations to Gelisim University Automotive Technologies Application and Research Center for supporting this study.

Credit authorship contribution statement

Haydar Kepekçi: Methodology, Supervision, Editing, Review.

Mehmet Emin Ağca: Investigation, Original drafting, Writing, Visualization, Graphics.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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