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MTU 16V 4000 M90 BRAND/MODEL DIESEL ENGINE EXHAUST SYSTEM DESIGN

Mehmet Avcu
Design Department,
İstanbul Naval Shipyard Command, Pendik, Istanbul
mehmetavcu@ymail.com

Şadi Kopuz
Figes A.Ş. Vice General Manager,
Ulutek Teknoloji Geliştirme Bölgesi,Görükle, Bursa
sadi.kopuz@figes.com.tr

Mehmet Teke
Figes A.Ş. CFD Projects Director,
Ulutek Teknoloji Geliştirme Bölgesi,Görükle, Bursa
mehmet.teke@figes.com.tr

Abstract

In this study, the design of the exhaust system belonging to MTU 16V 4000 M90 brand/model diesel engine has been realized. During the study of the design of the exhaust system; the three-dimensional model of the system has been constructed by using "ANSYS Workbench", the mathematical models via Finite Element Method (FEM) have been done via "ANSYS ICEM CFD" and, the Computational Fluid Dynamics (CFD) analyses covering back pressure and thermal analyses have been performed by using "ANSYS CFX 12" program [1]. For the design of the dry-type silencer belonging to the exhaust system, the acoustic characteristics have been determined by applying an ampirical methodology [2]. The design of the exhaust system has been finalized regarding the design criteria of MTU 16V 4000 M90 brand/model diesel engine given by the producer company and the outfitting of the engine compartment in which the diesel engine will be used. Besides that, the producings of the wet-type and dry-type silencers have been realized according to the silencer constructions driven from this study.

MTU 16V 4000 M90 MARKA/MODEL DİZEL MAKİNE EGZOZ SİSTEMİ TASARIMI

Özetçe

Bu çalışmada, MTU 16V 4000 M90 marka/model dizel makineye ait egzoz sisteminin tasarımı gerçekleştirilmiştir. Egzoz sistemi tasarımı yapılırken; sistemin üç boyutlu modeli "ANSYS Workbench" kullanılarak oluşturulmuş, Sonlu Elemanlar Metodu (SEM) ile yapılan matematiksel modeller "ANSYS ICEM CFD" ile gerçekleştirilmiş ve geri basınç ve ısıl analizleri kapsayan Hesaplamalı Akışkanlar Mekaniği (HAM) analizleri "ANSYS CFX 12" programı ile yapılmıştır [1]. Egzoz sistemi içinde bulunan kuru tip susturucunun tasarımı yapılırken, akustik bir tasarım metodolojisi uygulanarak akustik karakteristiği belirlenmiştir [2]. Egzoz sistemi tasarımı; MTU 16V 4000 M90 marka/model dizel makineye ait üretici firma tarafından verilen dizayn kriterleri ve dizel makinenin kullanılacağı gemideki makine dairesi yerleşimi dikkate alınarak son haline getirilmiştir. Ayrıca, egzoz sisteminde bulunan yaş ve kuru tip susturucuların imalatları, bu çalışma kapsamında ortaya çıkan susturucu konstrüksiyonlarına uygun olarak gerçekleştirilmiştir.

Keywords: *Exhaust system, silencer, muffler, back pressure, pressure loss, pressure drop, noise, acoustic, diesel engine.*
Anahtar Kelimeler: *Egzoz sistemi, susturucu, geri basınç, basınç kaybı, gürültü, akustik, dizel makine.*

1. INTRODUCTION

Nowadays, main propulsion systems in civil and military ships being newly built are generally diesel engine oriented regarding their sizes and usage purposes. Using diesel engines mostly as main power element has increased the importance of the technical specification of the diesel engine itself and its other during-and-after design belongings.

In this respect, designing and constructing the exhaust system and system elements, which are designed according to the diesel engine and ship to be mounted, belonging to diesel engines which are the main source of the air-borne and water-borne noise has become important. In Turkey, the exhaust system and system components, which is needed for diesel engines procured from foreign countries, to be used especially in warships are either purchased as a package directly from the foreign manufacturer or supplied from the foreign-origined exhaust system manufacturers [4]. So, to increase the national contribution share in warship projects and be an example to Turkish Defence Industry by designing and manufacturing these exhaust system components, which have not been yet designed and produced by national defence industry; in the scope of this study, for a warship project which has been still carried on at the present time, the design of the exhaust system has been realized and the silencers included in this exhaust system have been manufactured [4].

2. EXHAUST SYSTEM BACK PRESSURE AND THERMAL ANALYSES

For the designed exhaust system, regarding the exhaust outlet, which is finalized from the ship board section at sea level, to decrease the noise due to the exhaust system to the minimum level, a dry-type silencer has been considered in addition to the wet-type silencer which is necessary for decreasing the exhaust output temperature and infrared signature characteristic of the ship. Therefore, the exhaust system has been developed with dry-type and wet-type silencers as total.

Back pressure and thermal analyses of the exhaust system are done by two sections; the first section covers the from-the-diesel engine-outlet-to-the-dry-type-silencer-outlet part where one-phased flow occurs, and, the second section includes the from-the-dry-type-silencer-outlet-to-the-ship-board-outlet part where two-phased flow occurs. While the analyses are being carried out, SST (Shear Stress Transport) model has been used as a turbulence model and no-slip-wall condition has been utilized for all the surfaces of the exhaust system. The boundary and environmental circumstances referenced in analyses are shown below regarding the technical specifications of MTU 16V 4000 M90 brand/model diesel engine and the environmental conditions in which the ship will serve.

Table-1: Environmental and Boundary Conditions in The Analyses

Maximum Exhaust Gas Temperature	430 °C
Maximum Raw (Sea) Water Flow Rate	140 m^3/hour
Raw (Sea) Water Temperature	25 °C
Exhaust Gas Flow Rate	8,7 m^3/sec
Pressure at Exhaust Gas Outlet	0 Pa (as relative)
Specifications of Air at Temperature of 430 °C	
Density	0,4975 kg/m^3
Viscosity	3,39x10^{-5} kg/msec
Specific Heat	1075 J/kg°K
Heat Conduction Coefficient	5,24x10^{-2} W/m^2°K

Mean back pressure value derived from the results of the back pressure analyses to be done for the whole exhaust system has been compared with back pressure criteria (between 30-50 mbar) of the manufacturer company for MTU 16V 4000 M90 brand/model diesel engine. While the construction design and dimensions of the exhaust system and the silencer included in the system are being determined, in addition to the acoustic characteristic of the silencer, this back pressure criterion is also used as a guideline.

2.1. Back Pressure Analysis of First Dry-Type Silencer Model

In the first attempt for the design of the exhaust system, a reflective dry-type silencer model which has perforated tube and reflective chamber inside of it and suits for the outfit of the engine room has been considered. The mesh of the silencer has been modelled with tetrahedral element types and the number of elements and nodes and the views belonging to the silencer are shown below.

Table-2: Mesh Details

Number of Elements	1.978.631
Number of Nodes	326.755

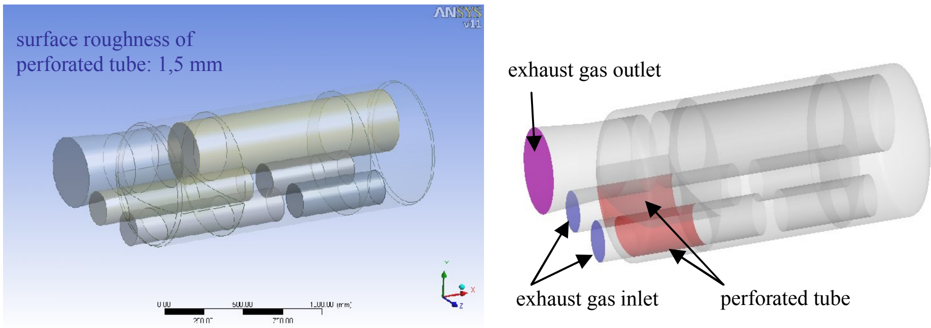


Figure-1: First Dry-Type Silencer Model

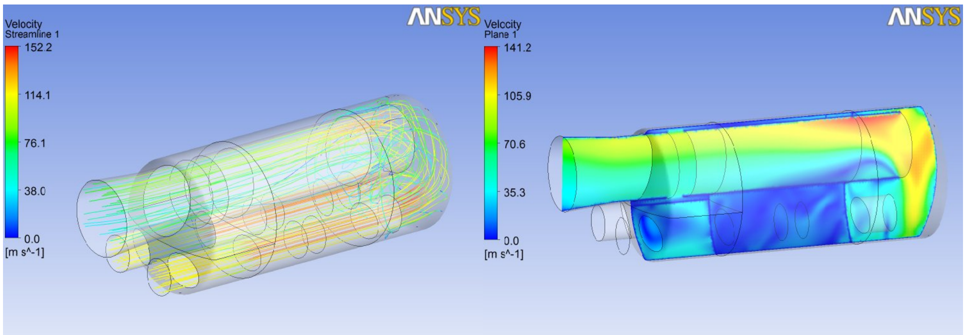


Figure-2: Stream Lines and Velocity Contours

Mean pressure drop (back pressure) value in this silencer is found as 6.370 Pa (63,70 mbar) from the result of pressure drop analysis using the environmental and boundary conditions given in Table-1 and pressure drop values which have been derived from the second section of the exhaust system (the section including wet-type silencer) the details of which is to be explained later. Even this pressure drop value derived from the dry type silencer has exceeded criteria value (between 30-50 mbar) given by the manufacturer company for the whole exhaust system. So it is determined that the design of this silencer is not suitable and it is decided to change the interior body and dimensions of the dry-type silencer.

This exceeding high back pressure value is found because the exhaust gas has been going back and forth the same way inside the silencer due to the exhaust gas inlet and outlet pipe circuits being at the same place, the exhaust flow velocity is high due to the small cross-section area of the inlet circuit, the exhaust flow velocity has been increased due to sharp turning when the exhaust gas has turned to the outlet circuit after completing its track and finally losses due to turbulent flow.

2.2. Back Pressure Analysis of Modified Dry-Type Silencer Model

In the scope of the exhaust system design, the design (dimensions and interior structure) of the dry-type silencer which is to be used in the system has been done by considering acoustic analyses which will be explained later in this paper and the layout of the engine room. Regarding also the exhaust outlet size of the diesel engine, the inlet pipe of the dry-type silencer has been designed in two different ways and the one of these two silencer geometries which gives the lowest pressure loss has been chosen as the geometry of the dry-type silencer.

The mesh of the silencer has been modelled with tetrahedral and prism (at wall) element types and the number of elements and nodes and the views belonging to the silencer are shown below.

Table-3: Mesh Details

Number of Elements	342.621
Number of Nodes	137.247

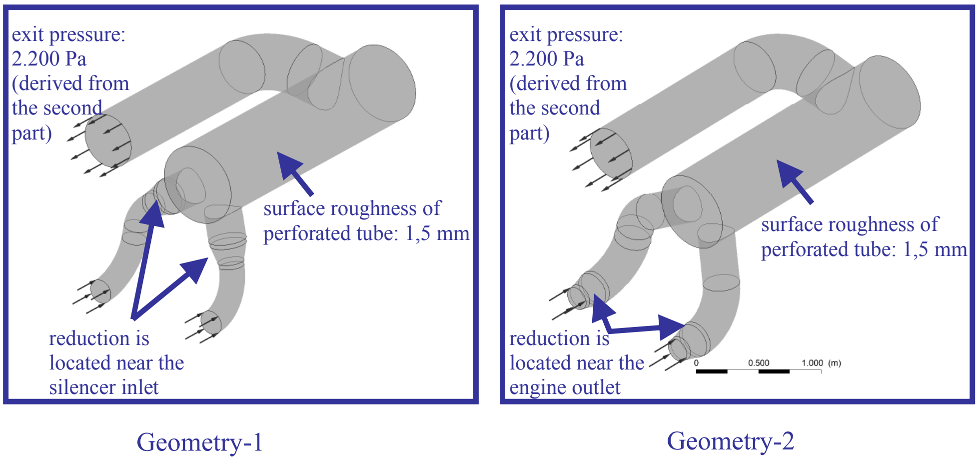


Figure-3: Modified Dry-Type Silencer Models

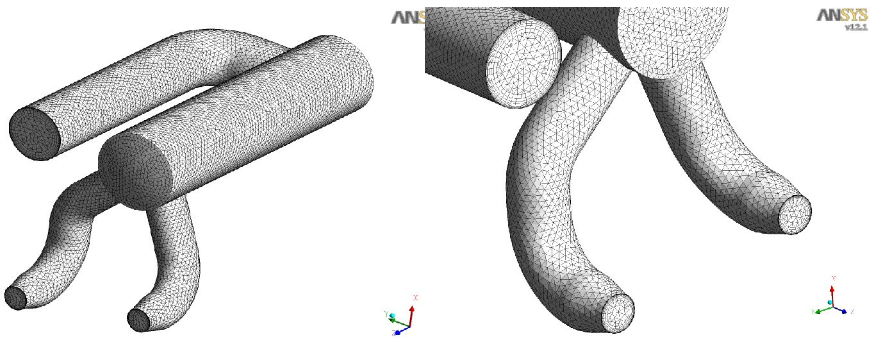


Figure-4: Modified Dry-Type Silencer Model Mesh (Geometry-2)

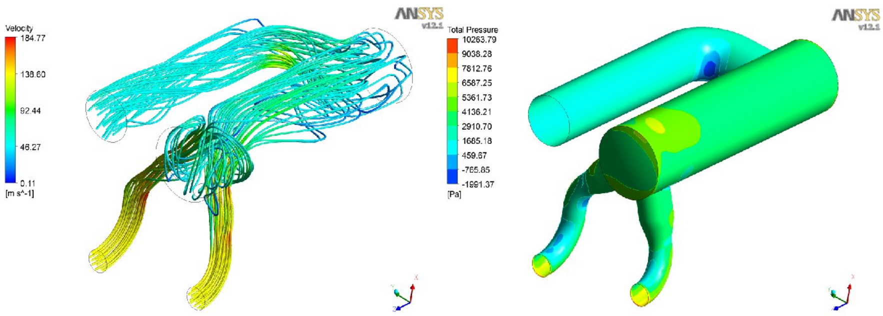


Figure-5: Stream Lines and Pressure Loss (Geometry-1)

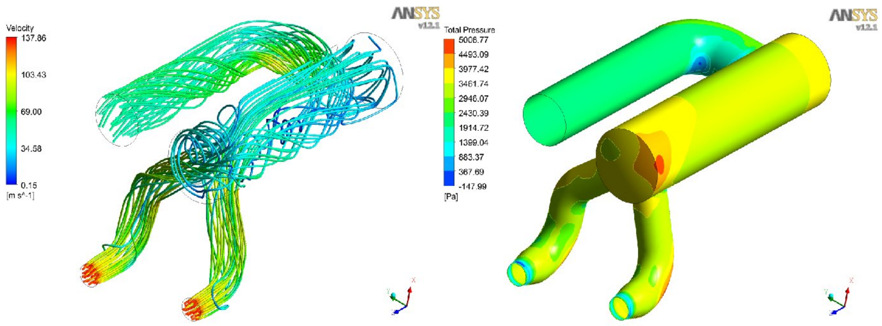


Figure-6: Stream Lines and Pressure Loss (Geometry-2)

Mean pressure drop (back pressure) values in the first and second geometries are found as 6.100 Pa (61,00 mbar) and 2.300 Pa (23,00 mbar), respectively, from the result of back pressure analysis using the environmental and boundary conditions given in Table-1 and pressure drop values which have been derived from the second section of the exhaust system (the section including wet-type silencer) the details of which is to be explained later. These back pressure values include the 0.5 mbar additional pressure drop resulting from the perforated pipe. When the results derived from the analyses are investigated, it is seen that the back pressure value found for Geometry-1 exceeds the manufacturer's criteria given for the whole exhaust system (30-50 mbar) and the pressure drop for Geometry-2 are within the limits. Considering the pressure drops found, it is decided that the silencer construction in Geometry-2 has been chosen as the final structure and will bu used in the exhaust system.

Table-4: Dry-Type Silencer Analysis Results

Silencer Model	Back Pressure (Pa (mbar))
First Dry-Type Silencer Model	6.100 (61,00)
Modified Dry-Type Silencer Model	**2.300 (23,00)**

In Geometry-1, the pipe circuit coming out of the diesel engine has the same cross-section area along the way to the dry-type silencer entrance and due to this cross-section area being small, the exhaust gas speed has increased in this part and so the pressure drop has been found high. In Geometry-2, the cross-section area of the pipe circuit coming out of the diesel engine is increased by using a fitting at the outlet of the engine unlike Geometry-1 and, thus the pressure drop has been lowered to required limits by reducing the exhaust gas speed below the speed in Geometry-1.

2.3. Thermal Analysis of Insulation Material

It is decided that, except the part after the wet-type silencer, the whole exhaust system will be covered with an insulation material to prevent high temperature arising on the exhaust system and affecting the crew of the ship. To determine the thickness of the insulation material, the thermal analyses have been realized regarding the minimum thickness of the insulation belonging to the dry-type silencer due to the layout conditions in the engine room. While utilizing the thermal analyses, maximum exhaust gas temperature (430 °C) and the thermal conductivity of the sheet metal of the exhaust system and the insulation material are taken into account.

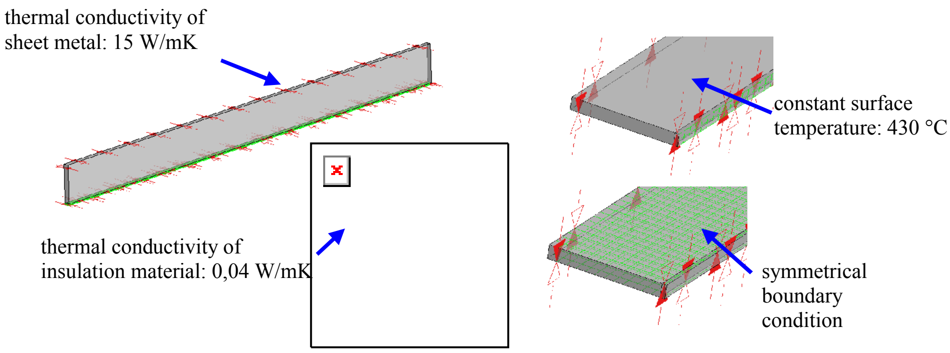


Figure-7: The Conditions in Thermal Analysis

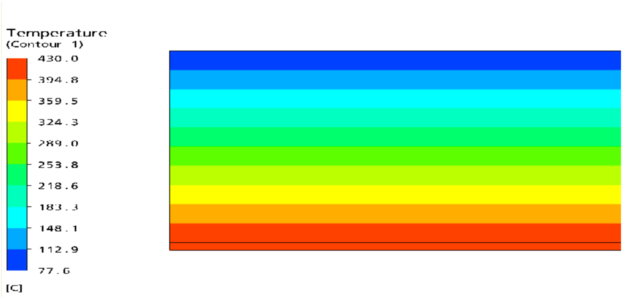
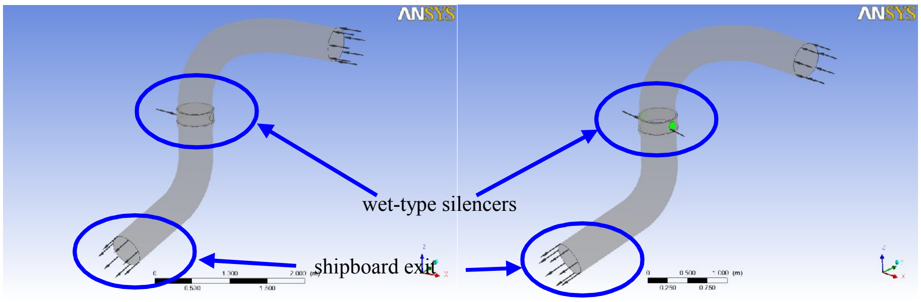


Figure-8: Temperature Distribution of Sheet Metal and Insulation Material

According to the thermal analysis, at the minimum insulation thickness, the surface temperature has been calculated as 77.6 °C. Considering the thickness will increase in the other parts of the exhaust system, the temperature value derived from the thermal analysis is considered applicable for the engine room.

2.4. Back Pressure and Thermal Analyses of Wet-Type Silencer Model

In the scope of the exhaust system design, to determine structure of the wet-type silencer which is to be used in the exhaust system, the wet-type silencer is designed as having the sea water inlet pipe and a perforated structure which enables mixing of the sea water and exhaust gas, attenuating the noise due to the exhaust via the sea water cooling and suitable for the engine room layout. By also considering the dimensions of the sea water pipe cross-section coming out of the diesel engine, four different models for wet-type silencer according to sea water inlets are designed. These different designs have been composed of single and double inlets and perpendicular and 45° inclined inlets. For these wet-type silencer models, back pressure and thermal analyses which the temperature of the mixing of the sea water and exhaust gas at the shipboard have been applied.



(a) Single İnlet (perp. and 45° inclined) (b) Double İnlet (perp. and 45° inclined)

Figure-9: Wet-Type Silencer Models

The mesh of the wet-type silencer has been modelled with hexahedral element types and the number of elements and nodes and the mesh views belonging to the silencer are shown below.

Table-5: Mesh Details

Number of Elements	232.260
Number of Nodes	242.402

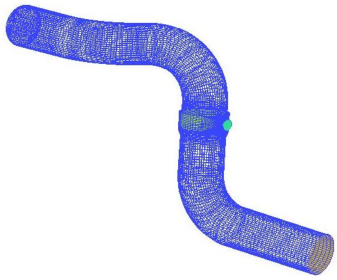
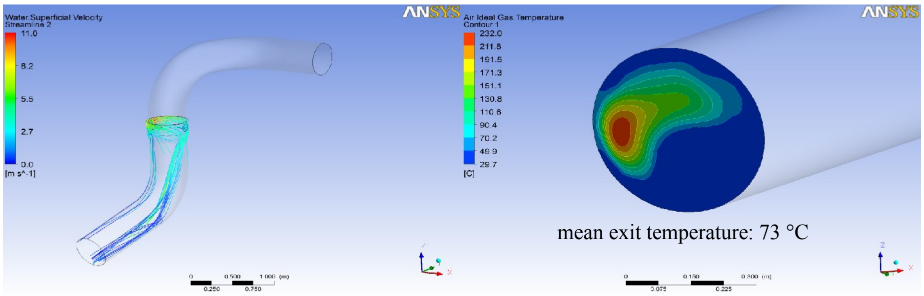
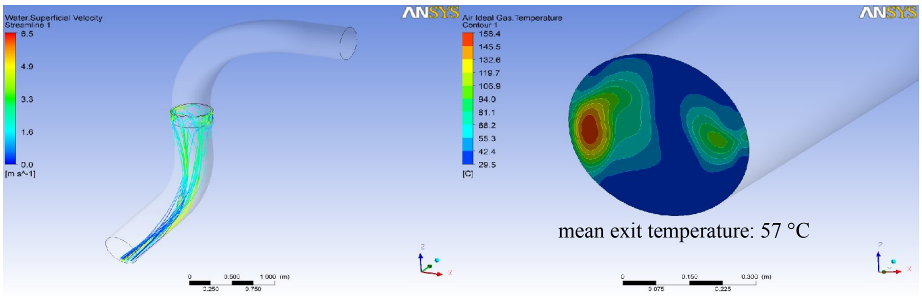


Figure-10: Wet-Type Silencer Model Mesh



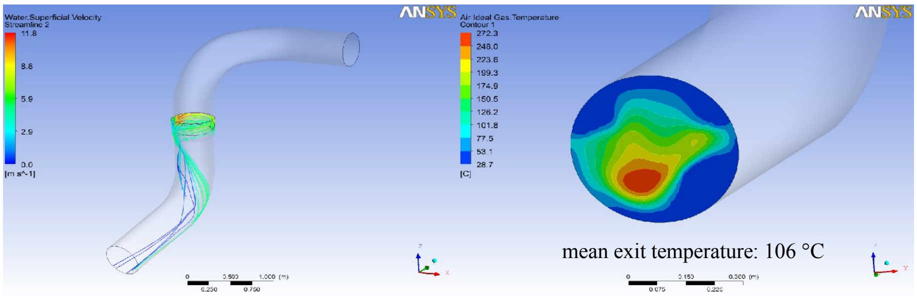
(a) Sea Water Streamlines (b) Temperature Contours at Shipboard Exit

Figure-11: Wet-Type Silencer Model for Single and Perpendicular İnlet Condition



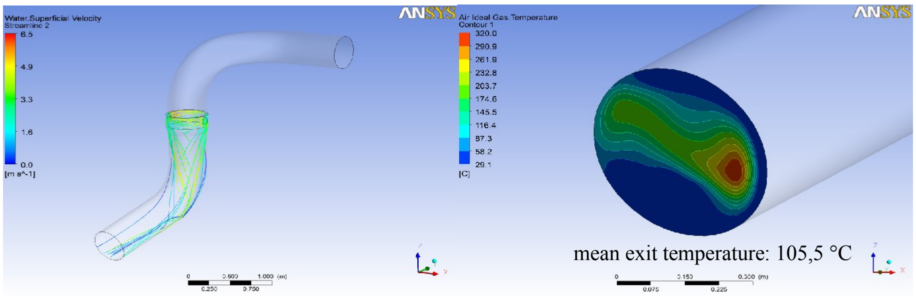
(a) Sea Water Streamlines (b) Temperature Contours at Shipboard Exit

Fifure-12: Wet-Type Silencer Model for Double and Perpendicular İnlet Condition



(a) Sea Water Streamlines (b) Temperature Contours at Shipboard Exit

Figure-13: Wet-Type Silencer Model for Single and 45° Inclined İnlet Condition



(a) Sea Water Streamlines (b) Temperature Contours at Shipboard Exit

Figure-14: Wet-Type Silencer Model for Double and 45° Inclined İnlet Condition

The values resulted from the back pressure and thermal analyses are given below for the four different configurations of the wet-type silencer using the environmental and boundary conditions given in Table-1. In order to reduce the infrared signature of the ship, regarding that the low board temperature is required by utilizing better heat transfer and, the noise attenuation is increased when cooling is sufficient, the one of four different wet-type silencers, which gives the lowest shipboard exit temperature and has double-perpendicular-inlet-configuration, has been chosen to be used in the exhaust system.

Table-6: Wet-Type Silencer Analsis Results

Silencer Configuraion	Back Pressure (Pa (mbar))	Mean Shipboard Temperature (°C)
Single Inlet-Perpendicular	2.271 (22,71)	73
Double Inlet-Perpendicular	**2.200 (22,00)**	**57**
Single Inlet-45° Inclined	1.444 (14,44)	106
Double Inlet-45° Inclined	1.493 (14,93)	105,5

Because the sea water flows into the wet-type silencer with a lower speed and normally to the surface, its time spent in the silencer increases and thus more heat transfer occurs due to better cooling of the exhaust gas. However, this situation has negative effects in back pressure values and as the heat transfer and cooling increases, pressure drop increases as well.

Table-7: Summary of Back Pressure Analyses of Dry and Wet-Type Silencers

<table>
<tr><th>Exhaust System Components</th><th>Back Pressure (mbar)</th><th>MTU 16V 4000 M90 Brand/Model Diesel Engine Back Pressure Criteria</th></tr>
<tr><td>Dry-Type Silencer</td><td>23</td><td rowspan="3">30-50 mbar</td></tr>
<tr><td>Wet-Type Silencer</td><td>22</td></tr>
<tr><td>Total</td><td>45</td></tr>
</table>

Total back pressure value resulted from the analyses of the whole exhaust system from the diesel engine outlet to the shipboard outlet containing dry and wet-type silencer, as seen in Table-7, has been found within the criteria of the diesel engine and, therefore it is decided that this exhaust system is applicable for MTU 14V 4000 M90 brand/model diesel engine.

3. EXHAUST SYSTEM ACOUSTICAL DESIGN

It is envisaged to use dry-type and wet-type silencers in the exhaust system to, especially, reduce the noise of the exhaust occurred inside the engine room due to the diesel engine [3, 5]. While the acoustical characteristics is designated, the dimensions and interior structure of the dry-type silencer which would attenuate most have been determined by applying a acoustical design methodology based on various parameters in the exhaust system [2]. This methodology has not been used for the wet-type silencer and the rest of the exhaust system, but it is considered that these components will contribute the attenuation.

Silencers as known are noise control components to reduce the noise of the diesel engine exhaust, fan and other noise sources where gas flow occurs [3, 5]. Silencers have been divided into two categories: passive silencers attenuate the acoustic energy with the reflective, absorptive (dissipative) method or combining both types and active silencers attenuate the noise using electronic feedforward or feedback techniques [3, 5]. The dry-type silencer belonging to the exhaust system in this study is also called as ‘muffler’ in the literature and is a passive type silencer due to its working principle (the wet-type silencer is also a passive type silencer structurally).

In the scope of the exhaust system design, to be able to design the dry-type silencer which is to be used in the system, a dry-type silencer model, which has a perforated pipe inside of it and has the reflective property and is suitable for the layout of the engine room, has been considered. This silencer performs the attenuation especially by absorbing due to the insulation material (rock wool) encompassing the perforated pipe.

The reasons of designing interior of the dry-type silencer in such a way are stated below [3, 5].

a. Having influence on wideband frequency interval due to absorbing property,

b. Providing more smooth attenuation at all frequencies of wideband by preventing tendency of sharp and sudden increase at various frequencies in this frequency interval and attenuation providing property in a narrow frequency interval which is only seen in reflective silencer,

c. Having property of providing much more attenuation at low frequencies (0-500 Hz), which is acoustic characteristics in reflective type silencers, due to having reflecting property as well as absorbing property and so providing attenuation more at low (firing) frequencies where the noise of the diesel engine is developed most.

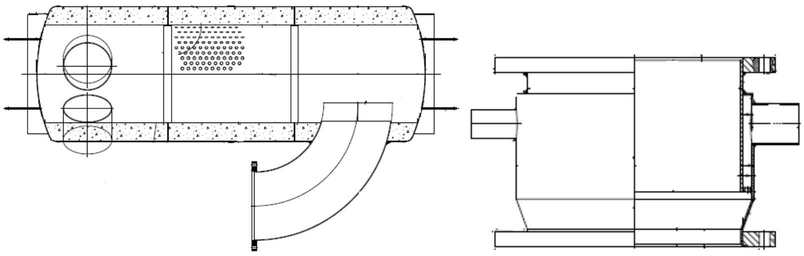
Absorbing type silencers can be designed with the rectangular cross-section or circular cross-section. Although the designing methodology is the same both, the silencer with circular cross-section provides almost two times more noise attenuation than the silencer with rectangular cross-section which has the same insulation material and same dimensions [2]. Therefore, it is decided for the dry-type silencer to be with circular cross-section.

For MTU 16V 4000 M90 brand/model diesel engine, the noise characteristics of the center frequencies belonging to 1/1 octave bands (Sound Pressure Level, SPL) is provided by the manufacturer company and, these center frequencies are based to determine the attenuation quantity. In the scope of the design methodology applied to the dry-type silencer, first, regarding the sound velocity (540 m/sec) occurred in the maximum exhaust temperature (430 °C) of the diesel engine, the wave length for each center frequency of 1/1 octave bands and Mach Number (ratio of the exhaust gas speed to sound velocity) have been calculated. By applying these parameters, the attenuation per length of the dry-type silencer has been determined and, the total attenuation value due to the dimensions and internal structure of it has been calculated by considering the inlet configuration of the dry-type silencer and by applying the corrections due to the expansion of the exhaust gas to occur inside of it [2]. In addition to these attenuation values, the distance correction because of the noise measurements to be done at 1 m and A-Weighted correction due to the human ear sensitivity to the frequency and sound pressure have been carried out and, the final attenuation value (SPL) has been found for the dry-type silencer in each center frequency. Total Sound Pressure Level (TSPL) value has been calculated by gathering applying the logarithmic addition method to both SPL values of each frequency taken from the manufacturer and resulted from the acoustic analysis and, then the noise reduction without regarding the frequency has been determined.

Table-8: Dry-Type Silencer Acoustic Analysis

TSPL (dBA) - Given	130,30
TSPL (dBA) - Attenuated	99,60
Noise Reduction (dBA)	**30,70**

The noise reduction stated above is obtained by using only the dry-type silencer and is enough for an exhaust system. Furthermore, in addition to the dry-type silencer which provides the highest attenuation, it is considered that other components of the exhaust system and the wet-type silencer contribute also to the attenuation [2]. The discontinuity points like the exhaust system pipe circuit, elbows etc. provide attenuation at all center frequencies of 1/1 octave band because of decreasing the acoustic energy of the flowing exhaust gas, even though causing the back pressure to increase [2]. The wet-type silencer has been mounted to the exhaust system to reduce the infrared signature of the ship by cooling the exhaust gas sufficiently and provide noise attenuation in the acoustic point of view. As seen in the back pressure and thermal analyses of the wet-type silencer, the back pressure is increasing while the heat transfer increases but the shipboard outlet temperature is decreasing as much. Therefore, the wet-type silencer which has the lowest board outlet temperature has been chosen from four different analyzed silencer types by taking into consideration that sufficient cooling increases the noise reduction. It is considered that the wet-type silencer, which provides attenuation mainly at high frequencies above 250 Hz of 1/1 octave band, increases the noise attenuation at the exhaust system in addition to the dry-type silencer [2].



(a) Dry-Type Silencer (b) Wet-Type Silencer

Figure-15: Technical Drawings Belonging to Dry and Wet-Type Silencers [6]

4. CONCLUSION

In this paper, the design of the exhaust system belonging to MTU 16V 4000 M90 brand/model diesel engine has been realized. The dimensions and internal structure of the dry and wet-type silencers which are the main components of the exhaust system and the physical properties of the insulation material have been determined based on acoustic, back pressure and thermal analyses and, the layout of the diesel engine in the engine room. The rest of the exhaust system components (sheet metal material, compensator, hanging apparatus etc.) are determined by considering the diesel engine, the designed silencers and the layout of the engine room.

From the results of the back pressure analyses, it is seen that the total back pressure in the whole exhaust system is within the limits of the given diesel engine criteria and, the board outlet temperature of the exhaust system is substantially low. It is determined that the noise which is produced from the diesel engine exhaust can be considerably lowered even though just the dry-type silencer is taken into account as shown by the acoustic analyses. It is assumed that this noise would be further reduced by the contribution of the rest of the exhaust system and the wet-type silencer.

The designed dry and wet-type silencers have been produced and the whole exhaust system has been outfitted to engine room compatibly. As further work, in order to validate the back pressure, temperature and acoustic characteristics resulted from the analyses; the tests for measuring these values will be conducted.

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