Exhaust Silencer

General

The pulsating flow from each cylinder's exhaust process of an automobile petrol or diesel engine sets up pressure waves in the exhaust system-the exhaust port and the manifold having average pressure levels higher than the atmospheric. This varies with the engine speed and load.

At higher speeds and loads the exhaust manifold is at pressures substantially above atmospheric pressure. These pressure waves propagate at speed of the sound relative to the moving exhaust gas, which escapes with a high velocity producing an objectionable exhaust boom or noise.

A suitably designed exhaust silencer or muffler accomplishes the muffling of this exhaust noise. The basics of silencing can be understood by recalling a few principles of physics. The velocity of sound in the gas at a given temperature is directly proportional to the square root of the product of the pressure and the ratio of the specific heats (at constant pressure to that at constant volume), and inversely to the square root of the density of the gas.

As the temperature varies, the velocity also varies directly as the temperature by another square root law involving the product of the coefficient of thermal expansion of the gas and the temperature. The exhaust noise can be reduced appreciably by providing resonance chambers to offset the noise wave effects.

This is accomplished by the principle of the Helmholtz resonator. In principle, it comprises the exhaust pipe, which goes through the large volume of a chamber.

The axial holes in the exhaust pipe enclosed by the chamber allow the gases to vibrate with the large mass of the gases in the chamber (forming a spring-mass vibrating system) and generate the sound of the same frequency but in opposite phase to that which has to be nullified (called anti-sound).

To achieve this the muffler volume should be proportioned to the engine piston displacement, and inversely proportioned to the engine speed and the square root of the number of engine cylinders. The usual length to diameter (l/d) ratio of the resonator is about 4:1 to 8:1.

A small l/d ratio muffler attenuates the sound well for a narrow frequency band, where as the large l/d muffler attenuates the sound to a lesser degree but over a wider frequency band. The effectiveness of the exhaust system in silencing the exhaust depends also on the relative lengths of the exhaust pipe (from the exhaust manifold to the muffler) and the tail pipe. A ratio of 1:2 is better than 4:1, and 1:1 is the poorest ratio.

Since the narrow frequency range limits the resonant chamber application, other features are incorporated in the resonant chamber to produce friction effects and filter off noise effects of other offending frequencies. Provision of baffles, resonator mufflers with end baffles, resonator with centre baffle chamber and four-chamber muffler are illustrative examples. In early stationary engines, muffling of the sound was accomplished by allowing the gases to expand by changing the direction of flow or by cooling them with injected water.

INTRODUCTION

Engine exhaust noise is controlled through the use of silencers and mufflers. Generally speaking, there is no technical distinction between a silencer and muffler and the terms are frequently used interchangeably. A silencer has been the traditional name for noise attenuation devices, while a muffler is smaller, mass-produced device designed to reduce engine exhaust noise.

SILENCER SELECTION FACTORS
The use of an exhaust silencer is prompted by the need to reduce the engine exhaust noise. In most applications the final selection of an exhaust silencer is based on a compromise between the predicted acoustical, aerodynamic, mechanical and structural performance in conjunction with the cost of the resulting system.

Acoustical performance. The acoustical performance criterion specifies the minimum insertion loss (IL) of the silencer, and is usually presented in IL values for each octave band as well as an overall expected noise reduction value. Octave bands and sound attenuation are discussed in further detail in Chapter 25. The insertion loss is determined from the free-field sound pressure levels measured at the same relative locations with respect to the outlet of the unsilenced and silenced systems. The IL of a silencer is essentially determined by measuring the noise levels of a piping systems before and after the insertion of a silencer in the exhaust stream. IL data presented by most manufacturers will typically be based upon insertion of the silencer into a standard piping system consisting of specified straight runs of piping before and after the silencer. Exhaust system configurations as well as mechanical design can have a substantial impact on the performance of and exhaust silencer and should be considered at the time of specification. Raw exhaust noise levels should be obtained from the engine manufacturer to determine the necessary noise reduction requirements of the proposed silencer. Specific installation conditions and exhaust noise levels will aid the manufacturer in determining the correct silencer to meet the required noise reduction.

Exhaust Silencers

If a silencer is located outside of the room or housing in which the engine is installed, one must be cognoscente of the effects of 'break-out' noise from either the silencer body or associated piping system. Breakout noise can dominate the stack radiated noise, particularly for high performance silencers that greatly reduce the noise transmitted downstream. A high performance exhaust silencer may have extremely good IL performance, but utilization of a thin walled piping system may allow substantial noise to be radiated from the piping system before entering the silencer body. The effects of sound transmission through a mass layer are discussed in Chapter 25. One solution avoids potential breakout from dominating the overall noise levels is to ensure a balance between the exhaust silencer shell thickness and corresponding piping. Manufacturers will often incorporate a multiple layer shell on higher-grade silencers to increase the transverse transmission loss of the silencer.

Aerodynamic performance. The Aerodynamic performance criterion specifies the maximum acceptable pressure drop through the silencer (backpressure of the silencer). The exhaust flow rate and temperature from the engine manufacturer are required to accurately predict the backpressure of a silencer and piping system. Selection of an exhaust silencer based solely on the diameter of the connecting piping can often lead to improperly selected products that may present installation issues. Traditional head loss calculations utilizing standardized coefficients for sudden contraction and expansion of fluids can be used to approximate the pressure drop through a silencer and combined with the values obtained for the remainder of the piping system. More complex silencer internal structures should be analyzed using Computational Fluid Dynamics (CFD) where traditional empirical calculations or assumptions may lead to inaccurate results. The pressure drop through silencers should be obtained from the manufacturer of the product upon submission of the required flow information.

Mechanical performance. The Mechanical performance criterion specifies the material properties of the exhaust system to ensure that it is durable and requires little maintenance when incorporated into service. Material selection is especially important in cases involving high temperature or corrosive gases. Traditional carbon steels will typically be sufficient for the majority of applications using Diesel fueled generators. Natural Gas engines will traditionally run at an elevated temperature above their Diesel counterpart, and may require a graded carbon or stainless steel that can maintain an element of structural performance at elevated temperatures. Aluminized steel is available from many silencer manufacturers and is often preferred for general applications. Aluminized steel is slightly more heat resistant than carbon steel and offers an increased resiliency to corrosion and is often selected as an economical alternative to specifying a stainless steel system. Regular periodic testing of a standby generator will subject the exhaust system to thermal cycles that can contribute to the premature corrosion of carbon steel.

Structural performance. The Structural performance criterion can specify the geometric restrictions and/or maximum allowable volume/weight of the silencer that can substantially influence the silencer design process. Secondary loading outside of the weight of the silencer can also affect the design and cost of the exhaust system. A standard engine silencer is not traditionally designed to absorb substantial loads due seismic activity, wind or thermal growth of adjacent piping. Silencers that are specifically incorporated as an element of an exhaust “stack” should be designed to accommodate the loads that will be absorbed due to potentially high wind loads as well as seismic activity. A commodity purchased silencer should be isolated from substantial piping runs through the use of flexible expansion joints to reduce or eliminate the transfer of loads and engine vibration. Customized silencers can easily be designed when the force and moment values that can be placed on a connection are indicated at the time of quotation.

SILENCER TYPES

Despite the terms and myriad of configurations, the silencer can be broken into three fundamental types: reactive (reflective), absorptive (dissipative), and combination reactive/absorptive. In addition to the three main silencer types, other functionality such as spark arresting, emission control, heat recovery, etc., may also be incorporated into the silencer design. Each type of silencer has specific performance attributes that can be used independently or in combination to produce the required IL for a specific application. A number of additional silencer styles and options are also reviewed in the following sections.

Reactive silencer. Reactive silencers generally consist of several pipe segments that interconnect with a number of larger chambers. The noise reduction mechanism of reactive silencer is that the area discontinuity provides an impedance mismatch for the sound wave traveling along the pipe. This impedance mismatch results in a reflection of part of the sound wave back toward the source or back and forth among the chambers. The reflective effect of the silencer chambers and piping (typically referred to as resonators) essentially prevents some sound wave elements from being transmitted past the silencer. The reactive silencers are more effective at lower frequencies than at high frequencies, and are most widely used to attenuate the exhaust noise of internal combustion engines. A generic reactive engine silencer comprised of two proportionally sized chambers with a pair of interconnecting tubes is shown below.

Absorptive silencer. Absorptive silencers contain fibrous or porous sound-absorbing materials and attenuate noise by converting the sound energy propagating in the passages into heat caused by friction in the voids between the oscillating gas particles and the fibrous or porous sound-absorbing material. The absorptive characteristics of materials are discussed in further detail in Chapter 25. Absorptive silencers usually have relatively wideband noise reduction characteristics at middle and higher frequencies. Absorptive silencers are often used to attenuate the engine intake noise or supplement the performance of reactive silencers for the engine exhaust noise control. The sound absorbing materials are generally held in position by the use of a perforated metal liner. Knowledge of the structural content of an exhaust system is important when considering the inclusion of a catalytic element or Selective Catalytic Reduction (SCR) system in conjunction with the silencer. Particulate migration of the insulation into the exhaust stream over a period of time can cause the catalytic element to become fouled and substantially impact or impede its performance.

Combination silencer. Some silencers combine both reactive and absorptive elements to extend the noise attenuation performance over a broader noise spectrum. Combination silencers are also widely used to reduce engine exhaust noise. Figure 19-1 shows typical noise attenuation curves of reactive, absorptive, and combination silencers.

Spark arresting silencer. Federal, state, local and municipal bylaws often dictating exhaust installations have provisions for arresting sparks from internal combustion engines. If an engine is to be used in an area where there is potentially dry vegetation of other combustible materials that are likely to be ignited by any hot carbon passing through the exhaust, one must incorporate spark-arresting capabilities into the silencer. Most approved spark arresting systems will employ diffusers or modified interconnecting tubes that create a centrifugal flow action in the exhaust to direct carbon particulate into a collection chamber. The particulate trap should be periodically inspected and cleaned to ensure proper functionality of the spark arresting capabilities of the silencer.

Catalytic silencer. To enhance exhaust gas emission control one may incorporate a catalytic converter element into a silencer to reduce the Oxides of Nitrogen (NOx), Carbon Monoxide (CO), and Non-Methane Hydrocarbons (NMHC) discharged in the exhaust stream. A catalytic converter is comprised of a NOx catalyst and an oxidation catalyst. The NOx beds reduce the NOx into benign N2 and H_2O, while the oxidation catalyst reacts with CO and HC to form water vapor and carbon dioxide. Inclusion of the catalytic element into the body of an exhaust silencer can reduce the cost of a combination system by eliminating the need for a separate acoustic silencer as well as a specialized catalyst housing and tracking system.

Heat recovery silencer. Most of the energy available in the fuel used in reciprocating and gas turbine engines is rejected in the form of heat. A reciprocating engine running at full load converts about one-third of the available energy into useful work, while the remaining twothirds of the available energy is lost in the form of heat rejection. In a prime power installation where the rejected heat can be used to provide energy to auxiliary applications a heat recovery silencer can yield attractive savings. Typical applications of heat recovery silencers for internal combustion engines include hot water heating, steam generation, heat transfer fluid heating, etc.

Tuned silencer. When the low frequency noise within a narrow band is extremely high, a tuned silencer can be designed to combat the specific offending frequencies. Tuned silencers consist of pipe segments and cavities that are used to produce a low frequency resonance at a required frequency. The accurate prediction of the tuned (resonance) frequency is extremely important to facilitate a match of the peak frequency for reducing the narrow band noise to a desirable level. A small deviation of the silencer resonance frequency from the peak frequency of the noise will greatly degrade the silencing ability.

Active silencer. Active silencing, or sound cancellation systems, employ detectors used in sensing the noise in an exhaust pipe and a loudspeaker that is used to reintroduce an inverted signal have been developed to reduce low frequency noise. The theoretical effect of reintroducing an inverted signal will result in complete elimination of sound from the exhaust silencer. Although the idea of sound cancellation is very simple and attractive, there are a variety of complications and problems arising from erratic fluctuations in the sound source. Active silencing is relatively expensive at the present time, and its acoustic attenuation performance at high frequencies is also limited. Widespread use will be dependent upon continued development of lower cost systems with improved performance realized through the use of better analytical algorithms, transducers and processors.

EXHAUST SILENCING SYSTEMS

System arrangement. A generic exhaust system collects hot exhaust gases from the engine and discharges them to the environment as quietly and efficiently as possible. An exhaust arrangement with minimized backpressure and satisfactory noise attenuation characteristics will usually be the result of a well-specified system. The exhaust termination points should not be in close proximity to the air intake system for the engine or the ventilation system of adjacent structures and should comply with all federal, state, and local regulations. Physical characteristics of the equipment room can also determine the specific configuration of an exhaust system layout and should be considered at the conceptual layout phase of the design.

Exhaust silencer. The most widely used structural shapes of silencers are the cylindrical configurations with end-inlet/end-outlet, side-inlet/end-outlet, and side-inlet/side-outlet. When a silencer is installed on top or inside of enclosure, the side-inlet/end-outlet configuration is most popular. This enables a minimum of piping. Hockey puck and rectangular shape silencers are used sometimes due to space limit. Silencers require traps to drain moisture. Traps installed at the lowest point of the silencer prevent rainwater from reaching the engine.

Exhaust Accessories. Most exhaust systems will be comprised of flexible connectors, connecting piping, an exhaust silencer, stack and rain caps. All exhaust systems must be isolated from the engine with flexible connections to reduce or eliminate the possibility of structural damage caused by cyclic vibration. A flexible connection is also used to isolate the weight of the exhaust system from the engine to allow relative shifting of exhaust components due to thermal growth. Thermal growth of exhaust piping must be anticipated and supporting members as well as fixed points should be placed to avoid excessive load on supporting structures and minimize transverse loading on the flex connector. The exhaust system shown in Figure 19-2 is referred to as a dual system that uses separate silencers and flow paths for each engine outlet. A flexible YConnector
may also be used to merge the exhaust gases from a dual outlet engine into a single inlet silencer where space permits. Mounting bands and supports should be designed to withstand all seismic, thermal and dead loads at the elevated temperatures that will be encountered during service. A wall or roof insulating thimble is generally required when the exhaust system passes through a combustible wall or roof and should be compliant with all applicable federal, state, and local fire codes. Rain caps are traditionally used to prevent precipitation from entering the exhaust system when the generator is idle.

Thermal insulation. Thermal insulation blankets may be needed to wrap the exhaust system to prevent excessive heat radiation into the generator room or to protect service personnel from exposure to extremely hot piping components. Flexible pipe connections, when insulated, must expand and contract freely within the insulation. The majority of insulation products traditionally used in engine exhaust systems consist of either an aluminum wrapped or a material clad insulation layer. Determination of the maximum exterior temperature of an insulated exhaust component will depend on many factors, and is often difficult to predict without specific knowledge of the exact service environment. Factors such as the ambient temperature and air flow across the piping elements can greatly affect the heat flux from the system and have a direct impact on the expected surface temperature of the system.

SYSTEM EVALUATION

System noise. It is extremely important to evaluate the total system when specifying an exhaust silencer for a specific installation. As we have discussed several factors such as breakout, raw source levels and spatial constraints can play significant roles in silencer selection and design. For example, a silencer might theoretically reduce the exhaust noise of an engine to 60 dBA at 10 feet without effectively silencing or isolating the engine intake, mechanical casing noise, etc. Many silencers have been incorrectly specified and installed in environments where the measured noise level in the area is considerably higher than the level produced by the silenced engine. A general knowledge of acoustics and sound will help in identifying potential factors that could impact the overall noise levels of an installation but a silencer manufacturer or acoustic consultant should be engaged when an unknown or difficult situation arises. As a final evaluation of an installed system the radiated sound pressure level at a given distance from the source should be measured and compared against the acoustical specification.

System backpressure. It is essential to the performance of a generator set that the installed exhaust system does not exceed the engine manufacturer's maximum exhaust backpressure limit. Pressure drop of exhaust system includes losses due to piping, silencer, and termination. High backpressure can cause a decrease in engine efficiency or increase in fuel consumption, overheating, and may result in a complete shut down of the generating systempotentially causing significant damage. Pressure drop is measured in a straight length of pipe 3 to 5 diameters from the last transition change after the turbocharger outlet.

REFERENCES

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