Abstract

The silencer or muffler is used to reduce the engine exhaust noise and also to reduce the exhaust flue gas temperature. To achieve this, a proper design of silencer is very important. The aim of this study is to find the effect of radial jets at the upstream of muffler on temperature and acoustic pressure. The radial jets were introduced at different reservoir pressure at the downstream of muffler. The simulation study has been carried out to determine the temperature and pressure distribution inside the silencer with and without radial jets and experiments were carried out to validate the result. It is observed that around 10 dB reduction in OASPL with interaction of jets in cross flow. These jets also reduces the exhaust gas temperature by 80 °C for engine speed 4000 rpm with jets at 2 bar reservoir pressure. Thus, this study concludes that the technique is effective to reduce the temperature of exhaust and noise. This technique can be applied easily to all vehicle mufflers where air at higher pressure is readily available as well as stationary engine mufflers using high pressure from small compressor.

Keywords: Cross Flow, Engine, Jets, Noise

1. Introduction

A device used to attenuate sound while also allowing fluid (usually gas) to flow through it, also known as muffler in British usage. Mufflers are extensively used to reduce the intake and exhaust noise from pumps, fans, compressors, and internal combustion engines. Although active noise control techniques are emerging, most mufflers continue to use passive silencing methods. Passive mufflers are categorized as reactive or dissipative based on their primary method of attenuation. Reactive mufflers reflect sound back toward the noise source, and dissipative mufflers use porous materials to absorb the sound. Internal combustion engines are typically equipped with an exhaust muffler to suppress the acoustic pulse generated by the combustion process. A high intensity pressure wave generated by combustion in the engine cylinder propagates along the exhaust pipe and radiates from the exhaust pipe termination. An exhaust system in a motorcycle consists of three parts namely exhaust header, exhaust tube and exhaust muffler as shown in Figure 1. In all muffler designs the tailpipe length can have an important effect. The tailpipe itself acts as a resonant cavity that couples with the muffler cavity.

1.1 Reactive Muffler

Reactive mufflers reflect acoustic waves at locations where a duct expands, contracts, or branches. Often a combination of reactive elements such as expansion chambers, resonators, and flow reversals are used. The reactive muffler is shown in Figure 2. Reactive mufflers can be designed to provide better low-frequency attenuation than a dissipative muffler of similar size. Also, reactive mufflers can be used in harsh environments that dissipative or active mufflers might not withstand.
In most cases, reactive mufflers are best suited for low-to-moderate frequencies, where acoustic wavelengths are larger than any cross dimension of the muffler. At these frequencies, mufflers can exhibit resonance or broadband attenuation behaviour.

1.2 Dissipative Mufflers
Dissipative mufflers use absorptive materials that dissipate the acoustic energy into heat. A variety of porous media can be used for absorption, with fibrous materials such as fibreglass being common as shown in Figure 3. The linings and baffles can be flat, contoured, constructed from layers of different materials, or mixed and matched for a particular application. Absorptive materials may face challenges due to harsh conditions such as high temperatures and potential clogging from particulate-laden flows. Dissipative mufflers are best suited for moderate-to-high frequencies, since absorption are less effective at low frequencies. At frequencies where the absorptive materials are effective, the attenuation are broadband, and the pass bands exhibited by reactive mufflers are reduced or eliminated. Compared to reactive mufflers of similar size, dissipative mufflers can have higher attenuation (except at resonances for the reactive muffler) and lower pressure drop. At higher frequencies, where the acoustic wavelength are smaller than the duct width, the attenuation of a dissipative muffler may decrease considerably.

1.3 Active Mufflers
Active mufflers attenuate unwanted noise by adding sound to counteract it. The disturbances add algebraically, resulting in a cancellation of the unwanted sound. An active muffler consists of sensors (such as microphones), a controller, and actuators (such as loudspeakers) as shown in Figure 4. Multiple microphones and multiple loudspeakers will be used in this type of muffler. The controller unit processes the signals from the sensor, and computes an appropriate signal for the actuator. Numerous control systems and strategies exist, and are under continuous development. Active mufflers are best suited for low frequencies where the sound field are relatively simple. The effectiveness of active mufflers has been demonstrated for a number of situations, but several challenges are the topic of ongoing research. There are a need for rugged sensors and actuators that can withstand high temperatures and harsh environments. Also, high-intensity disturbances at low frequencies require large-displacement, high-power actuators.

2. Jets In Cross Flow (JICF)
Jets in cross flow, also called transverse jets, and are central to a variety of applications like fuel injectors, smokestacks, film cooling of turbine blades and dilution holes in gas turbine combustors (Figure 5). In smoke stacks, the interaction between the jets and cross flow fluids affects the dispersal of pollutants into the atmosphere. Similarly, the dispersion of liquid effluents in streams and rivers affects the local concentration of pollutants in water. Clearly, both these examples are of environmental interest. The efficiency of a fuel injector is impacted by the mixing between the jets fluid (fuel) and the cross flow fluid (air/oxygen), and efficient mixing between the two is desired. Control jets are used to manage vehicles ranging from underwater submarines to aircraft, and constitute another example of jets in cross flow.

---

Figure 2. Reactive muffler.

Figure 3. Dissipative muffler.

Figure 4. Schematic of active muffler design.
Figure 5. Practical examples of jets in cross flow: (a) Contours of velocity inside a gas turbine combustor, (b) A smoke stack.

Figure 6. Schematic of a round jets in cross flow.

Figure 6 shows a schematic of a transverse jets. The jets fluid issues out of a round pipe and into the cross flow fluid travelling in the x direction. The schematic symbolizes a particular, and frequently observed, case of a round jets in cross flow, and one where the directions of the jets and the cross flow are perpendicular to each other. The jets trajectory is the path of the jets fluid as the jets bends and turns under the influence of the cross flow, and it is a first order quantity of interest. The parameter commonly used to describe a jets in cross flow is the velocity ratio \( r \), defined as:

\[
    r = \left( \frac{\rho_j U_j^2}{\rho_{cf} U_{cf}^2} \right)^{1/2}
\]  

which simplifies to

\[
    r = \frac{U_j}{U_{cf}}
\]

for constant density flows. Here, \( U_j \) is the jets velocity, \( U_{cf} \) is the velocity of the cross flow, \( \rho_j \) is the density of the jets fluid and \( \rho_{cf} \) is the cross flow fluid density. The diameter of the jets (exit d) is used to normalize the length scales in this flow.

The transverse jets has a complex flow field, quite different from that of a regular jets. It is composed of coherent, dominant, and distinctive vortical systems (Figure 7), which are summarized below:

2.1 Jets Shear Layer
These vortices are observed on the leading edge side (windward side) of the jets as a result of Kelvin Helmholtz instability. These ring vortices, similar to that observed in a regular jets, are unsteady and not observed in the mean.

2.2 Horseshoe Vortices
Also known as ‘necklace vortices,’ these are formed upstream of the jets and curve around the jets in the direction of the cross flow. This vortex system is similar to the horseshoe vortices observed in flow past a solid obstacle the cross flow boundary layer contributes to the vorticity of these vortices.

2.3 Wake Vortices
The system of wake vortices is observed downstream of the jets exit. They are oriented, roughly, in the initial direction of the jets, and extend from the leeward side of the jets toward the cross flow boundary.
2.4 Counter Rotating Vortex Pair (CVP)
The jets evolve to form a part of counter rotating vortices in the far field. The CVP is highly unsteady and is clearly visible only in the time averaged sense.

3. Experimentation Study

Figure 8 shows the experiment setup. The jets arrangement is used for single cylinder petrol engine muffler. The components of the setup are listed and explained below.

3.1 Experimental Setup
Experimental set-up consists of following parts:
1. Engine
2. Muffler
3. Single stage reciprocating air compressor.
4. A Bourdon pressure gauge.
5. A Transducer – Microphone.
6. FFT analyzer.
7. Thermometer (Pencil Type).
8. Tachometer

![Experimental setup (a) Line diagram and (b) Photograph.](image)

3.2 Experimental Methodology
After starting the engine, initially engine was kept on running condition for few minutes to attain its normal functioning mode. The rpm is measured with the help of tachometer and the engine running condition is adjusted to 3000 rpm. The sound pressure level at this point is measured using the microphone with the help of FFT analyzer and the temperature of flue gas is measured using the pencil type thermometer. Later the compressed air jets at the reservoir pressure of 1 bar, 1.5 bar and 2 bar is supplied into the jet manifold. By this circular type manifold, the air is supplied equally and at similar condition to eight different places each differing by 45° angle. After the introduction of jets, the sound pressure level as well as the temperature of flue gas is measured by FFT analyzer and pencil thermometer respectively. Similar steps are carried out for engine running at 4000 rpm.

Two working conditions of engine is considered. First, Engine running at 3000 rpm is considered because it constitutes to bike speed of 30 Km/h. Secondly, Engine running at 4000 rpm is considered because it constitutes to bike speed of 50 Km/h. The air jets which are introduced inside are at three different reservoir pressures, 1 bar, 1.5 bar and 2 bar. Two working conditions and three air jets conditions are considered. The temperature and noise measurement are carried out for all six combinations of air pressure.

3.3 Jets Arrangement
The Figure 9 stands out to be a clear representation of the jets arrangement manifold that are used in experiments. Such arrangements was necessary to be done in order to provide jets at eight different places equally. This arrangement can also be used when the total number of jets are increased further for future analysis. The arrangement of jets manifold contains the following components.

![Air jets arrangement.](image)
4. Simulation Study

4.1 Modelling of Muffler

4.1.1 Modelling of Available Muffler

The first step to start any simulation process is to create a 3D or 2D model. In this experiment the 3D model is been created first and it is been studied that the 2D design stands out to be the best suited one. Hence the later part of the studies is done using the 2D model. There is a inner tube in muffler which guides the flue gas flow. The muffler also contains a perforated tubes having four holes equally divided in all 360° space, each four holes placed at 90° to each other. The detail view of muffler can be seen in Figure 10.

The standard available muffler is of reflective type as shown in Figure 10, there are a total of five compartment separated by riveted plates. The muffler is 75 cm long. The 3D model of muffler along with the inner view is shown in Figure 10.

4.1.2 Modelling of Modified Muffler

The modification provided is the arrangement of air jets at normal atmosphere temperature. Eight air jets are introduced and each air jets are placed at an angle of 45° to each other. The air jets are provided with the help of jets arrangement manifold which are placed near the entry of the muffler inlet. The reason for placing the jets near the muffler inlet positions is to get better mixing of flue gas with air and to get better result. The arrangement of jets in 2D are shown in Figure 11(a) and Figure 11(b) gives a closer view of modified muffler. Since the simulation is done in 2D, only two air jets can be considered.

![Figure 10](image1.png)

Figure 10. 3D Model of available muffler.

![Figure 11](image2.png)

(a)

(b)

Figure 11. Modified muffler design (a) Full view (b) Closer view.

4.2 Simulation of Muffler

The temperature simulation of muffler is carried out using Ansys Workbench. The 2D simulation is considered and effective measures are taken into consideration. The meshing pattern used is quadrilateral meshing. The boundary conditions considered are according to the standard values whereas the temperature input given is as that of the measured value. Both modified as well as the available muffler is been simulated.

The simulation process can be divided into four parts.

- Simulation of available muffler (Without air jets)
- Simulation of muffler with air jets with reservoir pressure 1 bar
- Simulation of muffler with air jets with reservoir pressure 1.5 bar
- Simulation of muffler with air jets with reservoir pressure 2 bar

4.2.1 Simulation of Available Muffler (Without Air Jets)

The available muffler is simulated using Ansys Workbench. The inlet temperature provided is 450 K and the distribution of temperature is simulated. Nearby 14 reference point are considered along the length of the muffler and nearly 15 reference point are considered.
along the diameter of muffler to study the change in temperature. The simulated temperature distribution of available muffler are shown in Figure 12.

Figure 12. Available muffler simulation.

4.2.2 Simulation of Muffler with Air Jets at Reservoir Pressure 1 bar

Here the modification of muffler is been studied using simulation. The air jets are introduced at 1 bar reservoir pressure through the jets arrangement manifold. The introduction of air jets at 1 bar reservoir pressure helps in reducing the temperature of flue gas which in turn reduces the sound pressure level. The effect on temperature of flue gas due to interaction of air jets at 1 bar reservoir pressure can be seen in simulation by the reduction in temperature. The effect of introduction of jets at 1 bar reservoir pressure are shown in Figure 13 and Figure 14.

Figure 13. Modified muffler simulation at 1 bar reservoir pressure.

Figure 14. Closer view of mixing of air jets with flue gas.

The Figure 14 gives us the detail information of the effect of air jets into the muffler control system. The deviation of temperature due to the sudden impact with air jets at normal temperature are clearly shown in Figure 14. It is due to this air jets and flue gas interaction, the temperature of flue gas tends to decrease. The quality of mixing signifies better result.

4.2.3 Simulation of Muffler with Air Jets at Reservoir Pressure 1.5 bar

Here the air jets are introduced at 1.5 bar reservoir pressure by the provided air jets arrangement manifold. The introduction of air jets at 1.5 bar reservoir pressure helps in further reducing the temperature of flue gas compared to that of air jets introduced at 1 bar reservoir pressure, which in turn reduces the sound pressure level to further extend. The effect of temperature of flue gas due to interaction of air jets at 1.5 bar reservoir pressure can be observed in simulation by the reduction in temperature. The effect of introduction of jets at 1.5 bar reservoir pressure are shown in Figure 15.

Figure 15. Modified muffler simulation at 1.5 bar reservoir pressure.

4.2.4 Simulation of Muffler with Air Jets at Reservoir Pressure 2 bar

Here the air jets are introduced at 2 bar reservoir pressure by the provided air jets arrangement manifold. The introduction of air jets at 2 bar reservoir pressure helps in further reducing the temperature of flue gas compared to that of air jets introduced at 1.5 bar and 1 bar reservoir pressure, which in turn reduces the sound pressure level to further extend. The effect of temperature of flue gas due to interaction of air jets at 2 bar reservoir pressure can be observed in simulation by the reduction in temperature. The effect of introduction of jets at 2 bar reservoir pressure are shown in Figure 16.
5. Results and Discussion

5.1 Experimental Results

5.1.1 SPL Results

Figure 17 (a) shows the frequency spectra for engine speed of 3000 rpm and (b) shows the frequency spectra for engine speed of 4000 rpm. Here in this experiments, the obtained frequency spectra are of broadband nature and one single frequency does not dominate the research in order to decide the efficiency of the research. Since many frequencies of sound are involved, it is needed to calculate the overall sound pressure level to finalize the result of sound. Hence the decision step for judging the effect on sound are determined by calculating the overall sound pressure level.

5.1.2 OASPL

The overall sound pressure is calculated for all the conditions and the pattern of the result at 3000 rpm tallies (matches) with the desired result of sound pressure level decreasing as temperature of flue gas decreases. It can be clearly seen form Figure 18 that the addition of air jets at 1 bar reservoir pressure tends to decrease the sound pressure level by 1 dB which are about 0.7 % deduction. Later the air jets at 1.5 bar reservoir pressure tends to decrease the sound pressure level by 3.5 dB which are about 2.6 % in deduction. The air jets at 2 bar reservoir pressure tends to decrease the sound pressure level by 9.1 dB which are about 7 % of deduction. The addition of 2 bar reservoir pressure tends to decrease the SPL, compared with that of 1 bar reservoir pressure and 1.5 bar reservoir pressure air jets.

The pattern of the result at 4000 rpm tallies (matches) with the desired result of sound pressure level decreasing as temperature of flue gas decreases. The addition of air jets at 1 bar reservoir pressure tends to decrease the sound pressure level by 0.5 dB which are about 0.3 % deduction. Later the air jets at 1.5 bar reservoir pressure tends to decrease the sound pressure level by 7.07 dB which was out 5 % in deduction. The air jets at 2 bar reservoir pressure tends to decrease the sound pressure level by 10.5 dB which are about 7.3 % of deduction. The addition of 2 bar reservoir pressure tends to decrease the SPL, compared with that of 1 bar reservoir pressure and 1.5 bar reservoir pressure air jets.
5.1.3 Temperature Results
The Experimental temperature results for different engine conditions of 3000 rpm and 4000 rpm is been measured. As the reservoir pressure of air jets increases, the temperature of the flue gas tends to decrease. It has been observed that 20 K and 80 K reduction in temperature for 3000 rpm and 4000 rpm respectively with air jets at 2 bar reservoir pressure. The experimental results is shown in Figure 19.

5.2 Simulation Results
5.2.1 Pressure Results
For recording the readings and to compare the experiment, different reading points are considered along the length and even along the radius at certain distance after the air jets was introduced. This distance are taken into consideration so that the mixing of flue gas and air would come to a stable state. The probe points at which the readings are taken are shown in Figures 20 and 21. Figure 20 shows the reference location of lengths and Figure 21 shows the reference locations of radial.
The variation in pressure along the length and along the radius of muffler is simulated and the result is shown in Figure 22 and in Figure 23 respectively. In Figure 22 it can be noted that there was a drop and rise in pressure at the perforated tube exit location i.e at L8 position. These drop are because the flue gas expands at these location. i.e the exit of the perforated tube.

![Figure 23. Pressure distribution along radial positions, at positions shown in Figure 21.](image)

It is been observed that, the introduction of air jets tends to increase the pressure inside the muffler. The introduction of air jet at 1 bar reservoir pressure increases the pressure by 10 Pa at position 1. There is a difference of 25 Pa pressure at position 1 due to introduction of air jet at 2 bar reservoir pressure compared with without introduction of jets.

5.2.2 Temperature Results

Figure 24 shows the temperature variation along the length of the muffler for without jet and with jets at different reservoir pressure of air jets. It is seen that as the air jet pressure increases, temperature decreases along the length of the muffler. The temperature of flue gases reduced to 16 K and 25 K respectively at the location of 1 and 15.

![Figure 24. Temperature distribution along the length of muffler, at positions shown in figure 20.](image)

Figure 25 shows the variation in temperature along the considered radial positions for all different conditions of air jets as well as without air jets. It can be observed that without air jet the temperature at position 1 is about 412 K and when the air jet is introduced at reservoir pressure of 1 bar, the temperature at position 1 comes down to 353 K. The larger inclination of graph is observed at positions 1, 2, 3, 4 and positions 11, 12, 13, 14, 15 this is due to the interaction of air jets into the high temperature flue gas. This inclination shows the effect of mixing of air jets with the flue gas. As the reservoir pressure of air jets increases, the difference in temperature also increases.

![Figure 25. Temperature distribution along radial positions, at positions shown in figure 21.](image)
5.3 Comparison between Simulated and Experimental Result

Figure 26 shows the comparison between the simulated and the obtained experimental results. The temperature difference between the experimental results and simulated results varies in the range of 10 K to 20 K, whereas the temperature difference in terms of percentage between the experimental results and simulation results is 3 - 5 % in terms of K.

![Comparison between simulated and experimental result](image)

6. Conclusions

The Simulation and experiment study has been carried out to study the effect of jets on temperature of flue gases and noise. The effect of jet is clearly seen in the performance of muffler. As the jet pressure increases, temperature reduces due to mixing process taking place inside the muffler at very high velocity of jets. The jets at high pressure are very effective to reduce engine flue gas temperature with slight increase in pressure. The technique suggested to reduce noise and temperature is very effective and less expensive. This study focuses on radial air injection at one location, thus radial air injection at multiple location is a matter of future investigations.

7. References

1. Munjal ML. Analysis and design of mufflers—an overview of research at the Indian institute of science. Journal of Sound and Vibration. 1988; 211(3):425–33.
2. Bike Muffler. Available from: http://habal-habal.com/faq-motorcycle-aftermarket-exhaust-open-pipe-pd-96. Date accessed: 08/10/2014
3. E1-Sharkawy AI, E1-Chazly NM. A critical survey of basic theories used in muffler design and analysis. Applied Science Publishers Ltd. England, 1987.
4. Muffler Types. Available from: http://www.getdomainvids.com/keyword/reactive%20muffler/. Date accessed: 08/10/2014
5. Hwang Y, Lee JM, Kim S-J. New active muffler system utilizing destructive interference by difference of transmission paths. Journal of Sound and Vibration. 2003; 262:175–86.
6. Active Muffler. Available from: http://www.burnsstainless.com/muffler_technology_part_2.aspx. Date accessed: 08/10/2014.
7. Muppidi S, Mahesh K. Direct numerical simulation of turbulent jets in cross flow. Aiaa Aerospace Sciences Meeting and Exhibit. Reno, Nevada. 2005 Jan.