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Research Article

Control of noise and temperature using radial air injection inside engine silencer

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ABSTRACT

Silencer is a device mainly used for attenuation of the engine exhaust noise. Several modifications were attempted to improve the performance of a silencer. In this paper experimental and simulation study was carried out to determine the effect of radial air injection on the temperature and sound pressure level. The radial air injection is introduced in the form of jets inside the silencer. The design of available silencer was studied, and the 3D model was prepared using CATIA software. Simulation study was carried out using ANSYS Fluent, to determine the temperature distribution inside the silencer with and without modification. The radial jets at different pressure were introduced inside the silencer at three different locations. To acquire sound pressure level and temperatures at different locations, Lab View software and FFT analyser were used. The performance of silencer is analysed by comparing temperature of exhaust gases and sound pressure level at constant speed of 3000 rpm. With radial air jets of 2 bar reservoir pressure at three different location Overall Sound Pressure Level reduces by 6 dB and 42 K reduction in temperature of exhaust gases.

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INTRODUCTION

The vibrating body causes the medium (water, air, etc.) around it to vibrate and sound is produced. Sound waves consist of areas of high and low pressure called compression and rarefaction respectively. In automobile engine, the pressure waves are created when the exhaust valve opens repeatedly and gives out high pressure air into exhaust system. These pressures waves are the audible sound. The noise from the automobile is also due to vibration of engine body and transmission. Silencer helps to reduce engine noise as well as temperature of exhaust gases. Different design modifications were attempted to improve functionality of silencer. The reactive or reflective silencer used the phenomenon of destructive interference to reduce noise (1). Dissipative or absorptive silencers with absorptive material were used for absorbing sound energy. Active silencer system consists of a set of microphones and a speaker. The

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speaker was positioned in a pipe, which wraps around the exhaust pipe so that the sound from the exhaust comes out in the same direction as the sound from the speaker (2).

There were several modifications attempted to improve the performance of silencer. Jae-Eung and Kyung-Joon (3) used optimal design scheme by combining the Taguchi method and factorial design to improve silencer's capacity of noise reduction of the exhaust system. Ying-li Shao et al. (4) proposed a new concept of exhaust silencer using active cancellation phenomena. Deshmukh and Sharma studied the effect of radial air injection inside the combustor for suppression of thermo-acoustic instabilities (5-7). Brenda and Mark (8) used fluidic injection nozzles to inject air at the nozzle trailing edge in jets to reducing broadband shock noise. Nadar and Deshmukh (9) used air injection in one plane of silencer for reducing noise. Hsu and Ono (10) investigated the temperature dependence of acoustic emission accompanying the plastic deformation of austenitic stainless steel over the range 300 - 950 K. A local reaction model of the splitter material was employed, and analytical solutions and numerical results were presented for the sound intensity distribution within the silencer (11). Zhang et al. (12) studied the temperature dependencies of the surface acoustic wave (SAW) velocities and the elastic properties of thin metal films. Friend (13) reviewed the principles of sound propagation in fluid systems. Karagozian (14) studied the jets in cross flow or transverse jets as its relevance to a wide variety of flows in technological systems. Caeti and Kalkhwan (15) patented a noise reducer for reducing engine noise of a jet engine having a central axis and a main exhaust nozzle. Ellier et al. (16) concluded quantification of the changes in the velocity amplitudes due to the temperature gradient and highlighted the formation of one sole vortex in place of two. Jdidia et al. (17) studied the effect of the temperature and the frequency on the acoustic behaviour of lined duct partially treated with usual material used in acoustic insulation. Gul et al. (18) developed after treatment methodology based on the selective catalyst reduction system after the engine outlet. Şöhret (19) carried out study for sustainability measures to evaluate gas turbine aeroengine in order of energy efficiency, waste energy ratio, recoverable energy rate, energy destruction factor, and environmentaleffect factor and sustainability index. Muppidi and Maheshy (20) studied direct numerical simulation of turbulent jets in cross flow. Neuhaus and Neise (21) used steady air injection to improve the aerodynamic performance and reduce the tip clearance noise of axial turbomachines. Barbarino et al (22). Concluded that right combination of the fluid injection design parameters allows for a reduction of the jet-noise to 3.5 dB, as compared to the baseline case without injections.

The aim of this study is to reduce the engine exhaust gas temperature and engine noise by injecting radial air jets of different pressure at multiple locations along the length of silencer. To achieve this, experimental investigation for temperature and sound pressure level of available silencer is carried out. Based on data obtained, simulation study is carried out to understand the effect of radial air jets on temperature of exhaust gases. Based on the result, modifications in silencer are carried out for injecting air through manifold in the form of 8 radial jets at three different locations. The detailed experiments are performed for different air injection pressure and positions of radial air injection planes.

EXPERIMENTAL METHODOLOGY AND DATA ANALYSIS

The temperature of exhaust gas and engine noise of engine with standard silencer were recorded for 3000 rpm engine speed. Temperatures were recorded at the inlet, outlet, and 100 mm before reflective chamber. These values were used as boundary conditions for simulation of silencer in ANSYS Fluent. Simulation study was carried out in ANSYS Fluent for standard silencer and for modified silencer with one, two and three radial air injection planes. Experimentations for silencer were carried out with one, two and three radial air injections planes. The sound pressure level was measured using microphone and analysed with FFT setup. Also, temperatures were measured using K-type thermocouple and Lab VIEW setup. The experimental and simulation results were compared for different radial air injection plane.

To carry out experiments a 100 cc, four stroke engine of Bajaj CT100 was used. The standard silencer was modified for placing the radial air injection ports to inject air radially at three different locations. To provide radial air injection, an arrangement with 8 ports of 1 mm diameter were placed at 70 mm, 140 mm, and 210 mm respectively from the inlet end of silencer pipe. The experimental setup is shown in Figure 1. It consists of an engine, silencer, compressor, and radial air jet injection arrangement. Bruel – Kjaer brand microphone of frequency range 20 Hz – 20 kHz and a dynamic range of 16.5 dB – 134 dB was used for acoustic measurement. To capture acoustic signal, microphone was kept at the middle point of silencer at 300 mm and vertical

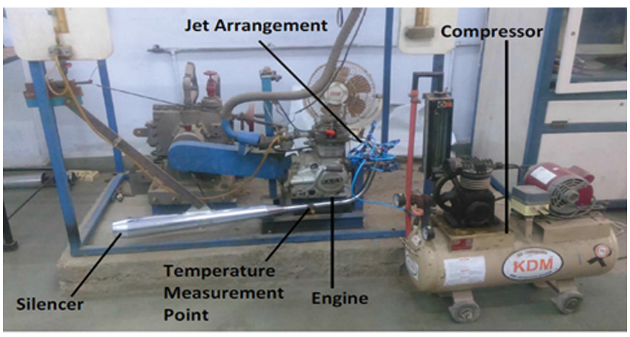

Figure 1. Experimental Setup.

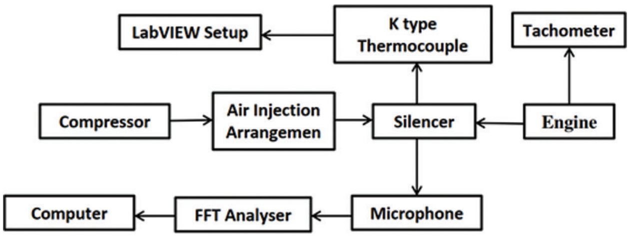

Figure 2. Line Diagram of experimental setup.

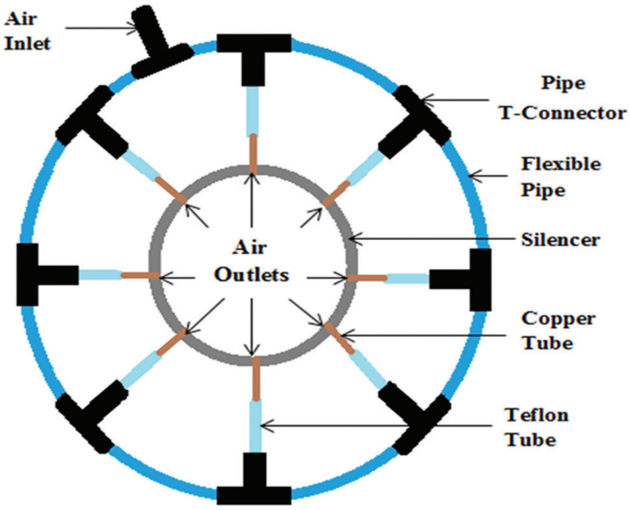

Figure 3. Radial air injection arrangement.

height of 150 mm from the ground. K-type thermocouples, made of chromel-alumel with the range of 0 to 600°C of accuracy 1°C, were used for temperature measurements. Kusam Meco brand tachometer of 1000 rpm to 19999 range with resolution of 1 rpm was used for speed measurement. The data acquisition system of National Instruments, NI USB-6211 and Lab VIEW software 7.1, were used as interface between all the sensing devices and the computer. The line diagram for the experimental setup is as shown in the Figure 2.

After running engine for 15 minutes at constant speed of 3000 rpm (as rated speed of engine 4500 rpm for maximum torque) the sound pressure level was measured using microphone and temperature was measured using K-type thermocouple without any modifications of silencer. Later the modifications were done to the silencer to provide radial air injections at three different locations. To reduce the temperature of exhaust gases, radial air injection should be closed to the entry point of exhaust gases. Therefore, the position of three radial injection planes are at a distance of 70 mm, 140 mm and 210 mm from the inlet end of silencer pipe. Arrangement used for radial air injection is as shown in the Figure 3. Each air injection plane has eight air injection ports which radially inject air in the silencer at eight points. The air was supplied at the rate of 2, 4 and 6 LPM to manifold through flow control valve at reservoir air pressure of 1 bar, 1.5 bar and 2 bar. The sound pressure level and temperature were measured for the silencer with one plane of air injection for reservoir air pressure at 1 bar, 1.5 bar and 2 bar while keeping the engine rpm at 3000 rpm. Again, the readings were taken at reservoir air pressure of 1 bar, 1.5 bar and 2 bar with two planes of air injection and three planes of air injection. Thus, there were total nine combination of injection planes and reservoir air pressure.

Calculation of OASPL

The overall sound pressure level (OASPL) provides a measure and, for 1/3 octave band specifications, can be calculated as the decibel equivalent of the root sum square (RSS) pressure. It provides a measure of the overall acoustic noise intensity. Sound Pressure Level (SPL) Spectrum is simply a logarithmic representation of S(f). It is calculated using Equation (1) and its unit is dB/Hz.

$$\mathrm{SPL(f)} = 10 \log_{10} S(f) \tag{1}$$

For calculating OASPL, the total energy contained in the spectrum is calculated using Equation (2) and integrate over all resolved frequencies. For calculation OASPL Equation (3) is used and its unit is dB.

$$E = \int S(f)df \tag{2}$$

$$\mathrm{OASPL} = 10 \log_{10} (E) \tag{3}$$

COMPUTATIONAL METHODOLOGY

Simulations were carried out using ANSYS Fluent to understand the effect of radial air injection on temperature and pressure distribution in the silencer. The 3D model of available silencer was prepared by taking geometry and dimensions of actual silencer that was used for experimentation. The available silencer was reflective type and has five compartments. The compartments ware separated by the riveted plates. The flue gases from engine run into first compartment through a pipe. This pipe after entering first compartment has perforations on it along its length. The flue gases pass through different compartments through the holes in the plates separating the compartments. The detailed view of silencer is shown in Figure 4.

Different models of modified silencer were developed to accommodate radial air injection planes. First model has arrangement for air injection radially through 8 holes at 70 mm from the inlet end of silencer pipe while second model has additional radial air injection plane at 140 mm from the inlet end retaining the earlier arrangement. Third model has additional radial air injection plane at 210 mm from the inlet end of silencer while retaining the earlier model of two plane as shown in Figure 5.

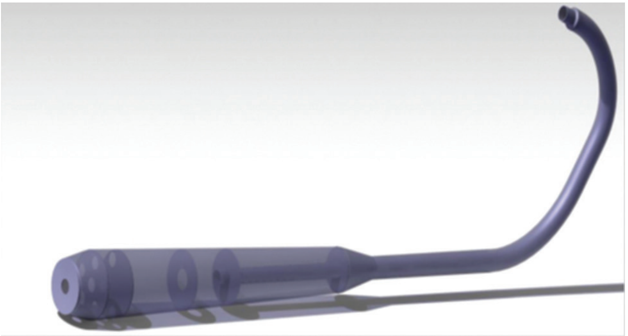

Figure 4. 3D model of standard silencer.

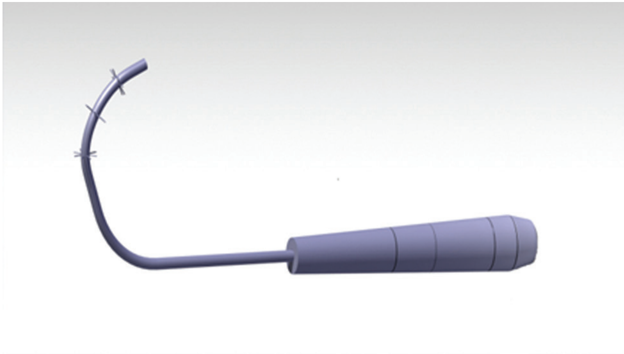

Figure 5. Modified silencer model with air injection in three planes.

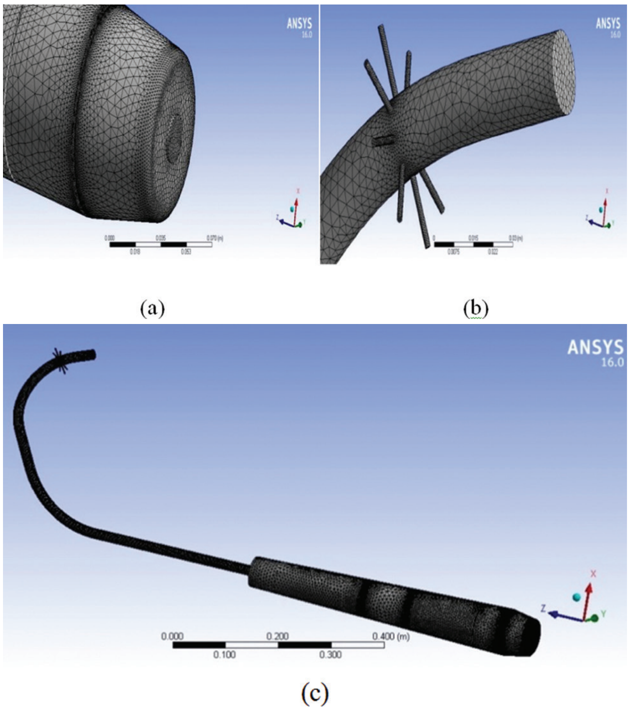

Figure 6. Meshing of silencer (a) Closer View at end of silencer. (b) Closer view at air injection. (c) Overall silencer mesh for single air injection plane.

After importing the CAD model in ANSYS, meshing was done. For meshing tetrahedral mesh was used. The skewness for tetrahedral mesh was kept below 0.9. Grid independent study was performed with different number of nodes and elements. Satisfactory results were obtained for different cases for the number of nodes and elements shown in the table below. With further increase in the number of elements there was no significant improvement in the results. Hence, to optimize the computational cost grid size was restricted to the number of elements and nodes given in the Table 1. Few views of meshed models of silencer are shown in Figure 6.

Table 1. Details of number of elements and nodes used in simulation study

Case	No. of elements	No. of nodes
No impingement	754559	166954
Single impingement	795909	176803
Double impingements	835586	185696
Three impingements	874435	194734

The boundary conditions of temperature and pressure were according to measured values from initial experiments and taken as 706 K and 10 bar respectively. The reservoir pressure and temperature of radially injected air was taken as 2 bar and 300 K respectively. To understand the effect of number of air injection plane, simulations were carried out for no air injection, one plane of air injection, two planes of air injection and three planes of air injections. Simulations parameters were set for the standard silencer. There were eleven reference points considered along the length of silencer to study the temperature and pressure change in the silencer. For simulation of silencer for one plane of air injection, air was injected radially through eight holes in the silencer at 70 mm from the flue gas inlet end of the silencer. All the parameters were kept same as that of the first simulation. For simulation of silencer for two planes of air injection, air was injected radially through eight holes in the silencer at two locations at 70 mm and 140 mm from the flue gas inlet end of the silencer. For simulation of silencer for three planes of air injection, air was injected radially through eight holes in the silencer at 70 mm, 140 mm and 210 mm from the flue gas inlet end of silencer. The inlet air is at room temperature i.e. 300 K and pressure of 2 bar.

RESULTS AND DISCUSSION

Experimental Results

The frequency spectra for different conditions at engine speed of 3000 rpm are shown in Figure 7. In this

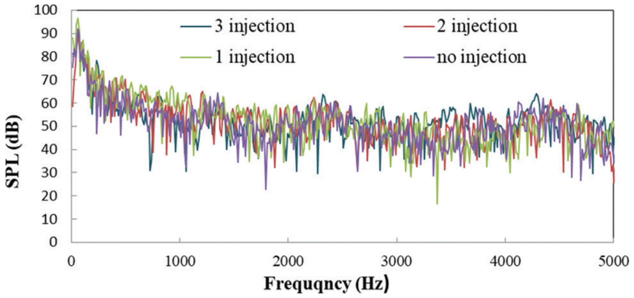

Figure 7. Frequency spectra for engine running at 3000 rpm with air injection at one, two and three planes.

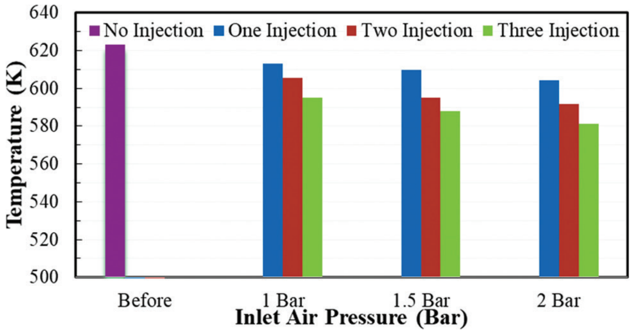

Figure 9. Temperature Results for all cases.

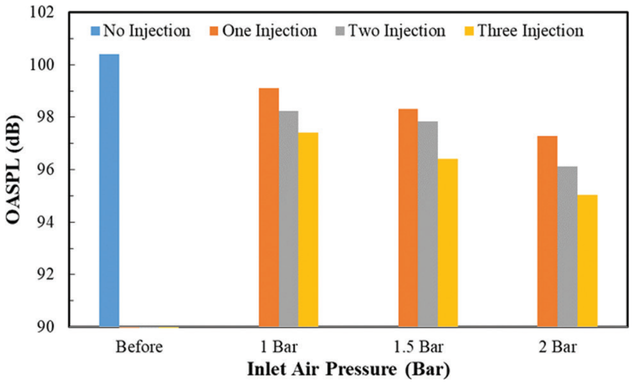

Figure 8. Comparison of OASPL for all three cases.

experiment the spectra obtained are of broadband nature and no single frequency dominates the results. As the frequency of the combustion noise concentrated at the range of 2000-3000 Hz and from initial experiments it was found that no high frequency noise observed beyond 5000 Hz. Therefore, in this study frequency range is restricted to 5000 Hz. To understand the effects of radial air injection on engine noise, sound pressure level up to 5000 Hz is consider obtaining OASPL.

OASPL are calculated for all four cases viz. no air injection case, air injection at one, two and three planes. The OASPL for silencer with and without any modification were calculated for engine running at speed of 3000 rpm for comparison. The OASPL for no air injection is 100.4 dB as shown in Figure 8. The impact between the injected jet and the main flow of exhaust gases, cause a locally rupture of the vortical structures and an increase of turbulence at outlet, i.e., at high frequencies, and a reduction of the turbulence in the downstream domain, which manifests itself as noise reduction at low frequencies [22]. The addition of air radially at first plane at 1 bar tends to decrease the sound pressure level by 1.3 dB which is nearly 1% reduction. Further the sound reduces by 2.09 dB for air injection at 1.5 bar which is 2.08% reduction. The air injection at 2 bar reservoir pressure tends to decrease sound by 3.12 dB which is about 3% of reduction. As the pressure increases the radial jets gets penetrates into the exhaust gas cause rupturing of vortical structures, this help to reduce turbulence in the downstream and reduces the sound pressure. For air injection in two planes, the addition of air radially at first and second plane at 1 bar tends to decrease the sound pressure level by 2.17 dB which is nearly 2% reduction. Further the sound reduces by 2.57 dB for air injection at 1.5 bar which is 2.5% reduction. The air injection at 2 bar reservoir pressure tends to decrease sound by 4.27 dB which is about 4.2% of reduction. Addition of radial air jets at multiple locations helps to reduce turbulence at the downstream of silencer without rise in back pressure. For air injection in three planes, the addition of air radially at first, second and third plane at 1 bar tends to decrease the sound pressure level by 2.98 dB which is nearly 2.9 % reduction. Further the sound reduces by 4 dB for air injection at 1.5 bar which is 3.9 % reduction. The air injection at 2 bar reservoir pressure tends to decrease sound by 5.37 dB which is about 5.3 % of reduction.

During an experimentation, for measuring temperature of mixture of flue gases and injected air, the temperature was measured at a location which is 100 mm before the reflective chambers. For no air injection the temperature at this point is found to be 623 K. The air at atmospheric temperature is injected in the form of radial jets into the stream of hot exhaust gases inside silencer, mixing of cold air with hot gas took place. This results into reduction in exhaust gas temperature. Addition of radial air injection planes and increase in reservoir pressure increases the quantity of cold air. This help to further reductions in the exhaust gas temperature. Temperature drops of 10.18 K, 18.41 and 28.88 K is observed at 1 bar reservoir pressure for one injection, two injection and three injection planes respectively. Temperature drops of 13.17 K, 27.87 K and 35.09 K are observed at 1.5 bar reservoir pressure for one injection, two injection and three injection planes respectively. Also, for reservoir pressure of 2 bar, temperature drop of 18.69 K, 31.33 K and 41.77 K for one injection plane, two injection planes and three injection planes respectively. The temperature comparison is shown in Figure 9.

Simulation Results

The temperature contour plot of standard silencer cut section through center along with reference points is shown in Figure 10. The point L4 on silencer in simulation is the point where the experimental temperatures are recorded. The simulation result of hydrodynamic pressure inside the silencer along its length are shown in Figure 11, for engine rpm of 3000 and radial air injection pressure at inlet reservoir pressure of 2 bar. It is seen that the pressure drops and rises at point 6 and point 8. This is because gas expands at the perforated tubes at point 6 and at point 8 as the hole on riveted plate separating the compartments. The locations of air injections for all the three cases are located between points L1 and L2. It is observed that introduction of jets tends to increase the pressure inside the silencer. Also, as the number of locations of air injection increase, the pressure also tends to increase slightly. The introduction of air jet increases the hydrodynamic pressure by 25 Pa, 29 Pa and 34 Pa for one, two and three injection planes respectively compared to no air injection case. As the pressure rise inside the silencer is very low, this will not have any adverse effect on engine performance.

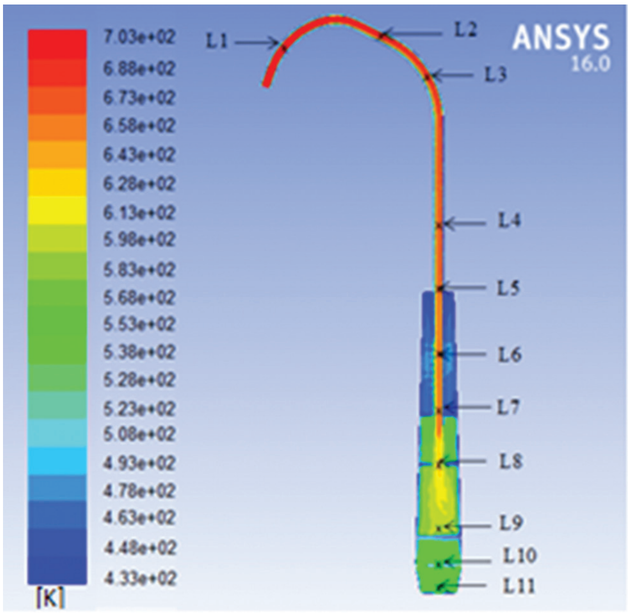

Figure 10. Temperature variation plot of Standard Silencer with reference points.

The temperature variation along the length of silencer for three cases of air injections are compared to no air injection in Figure 12. From the simulation results it is observed that temperatures are reduced by 34.26 K, 58.59 K and 80.89 K at location 4 for the air injection in one, two and three planes respectively at 2 bar reservoir pressure. There is more change in slope of temperature lines between point 1 and 2 in all the cases compared to the no air injection case. This indicates that there is a drastic reduction in temperature in this region due to addition of radial air injection.

The temperature contour plot for air injection in one plane is shown in Figure 13. Figure 13(a) shows the temperature contour at a location 10 mm before injection plane. It is complete red which indicates hot flue gas temperature which is close to 700 K.

The temperature contour in Figure 13(b) shows the injection plane where there are eight blue regions representing eight points where air at room temperature is being injected. Further there is mixture of injected air and hot flue gases giving different color contours. Figure 13(c) is the temperature contour of the plane at point 150 mm after L1. This figure shows that there is a significant reduction in temperature of flue gases due to mixing of injected air. The temperature at center is around 680 K. For air injection at two planes, temperature contours

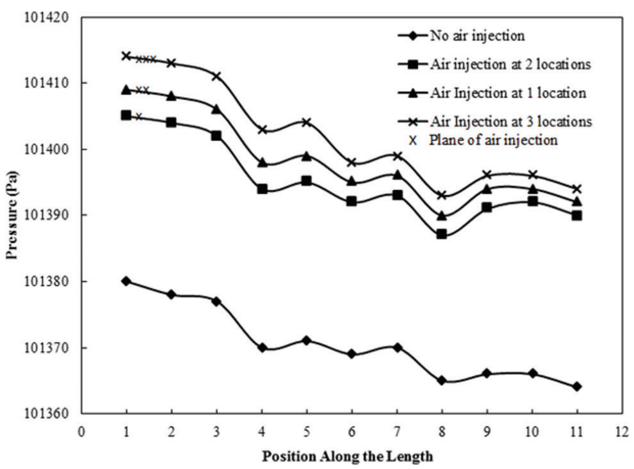

Figure 11. Hydrodynamic pressure distribution along the length of silencer.

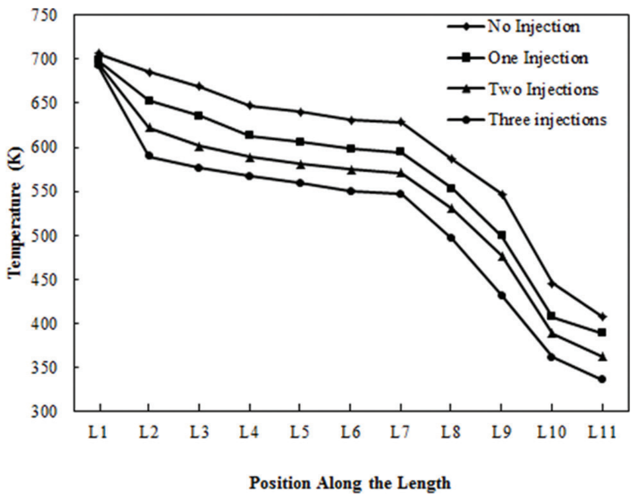

Figure 12. Temperature distributions along the length of silencer.

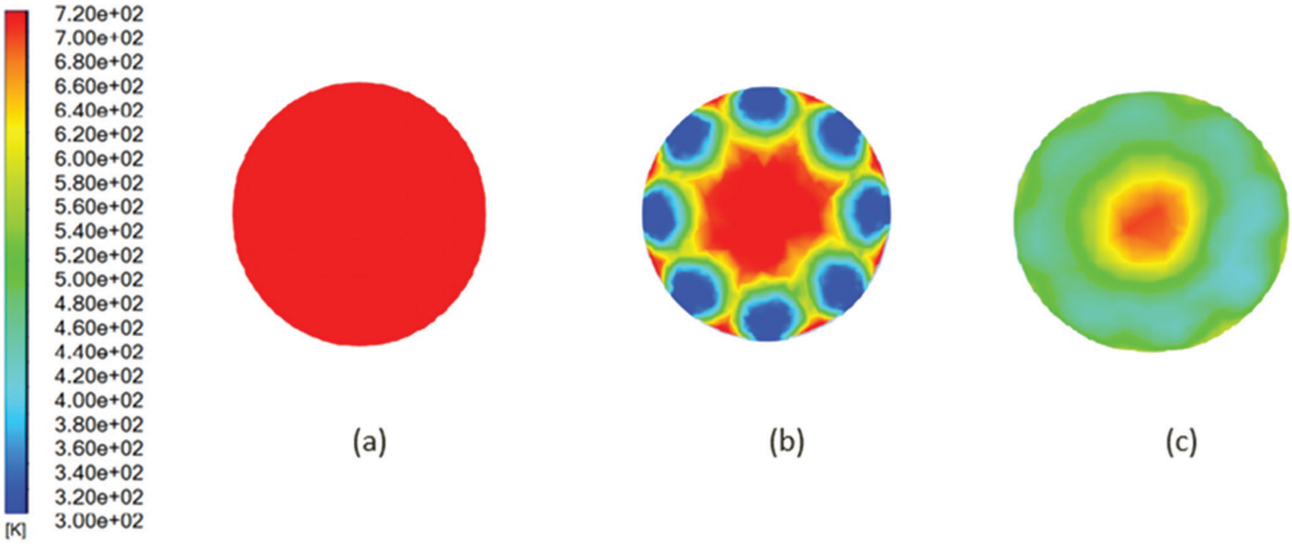

Figure 13. Temperature contours of silencer cross section for air injection at one plane.

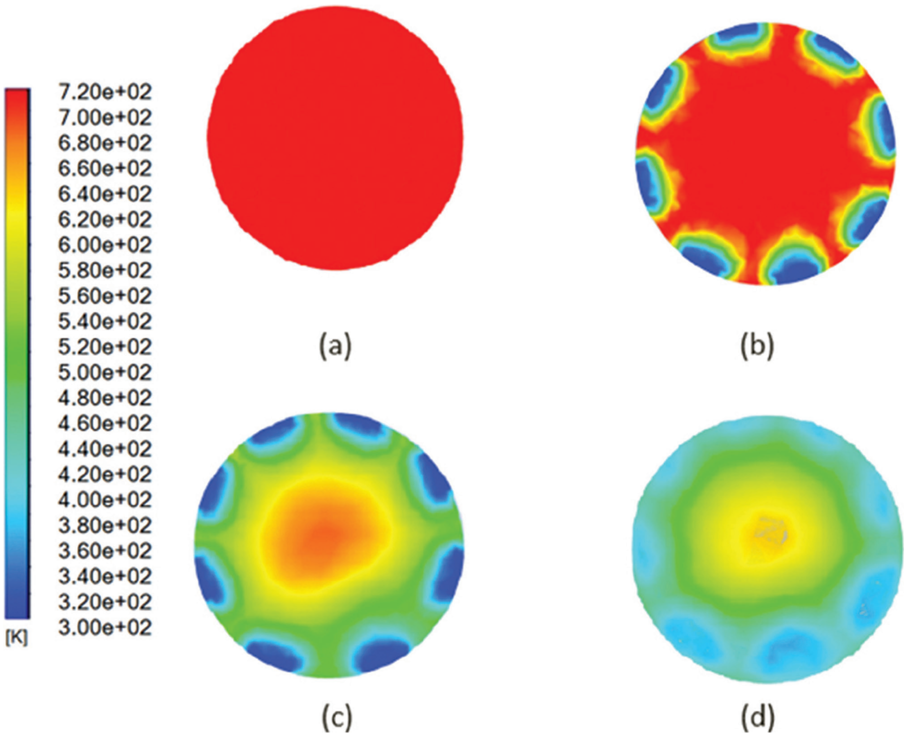

Figure 14. Temperature contour of silencer cross section for air injection at two planes.

for each plane are shown in the Figure 14(b) and 14(c). Compared to radial air injection at one plane, large reduction in temperature is observed for radial air injection at two planes.

In these temperature contours blue regions shows the points of air injection which is at room temperature of about 300 K. The temperature reduces significantly due to mixing of air injected and flue gases inside the silencer. Figure 15(d) shows plane at 150 mm from point L1. The temperature at center in this contour is around 650 K. Temperature reduces drastically for air injection at three locations compare to no air injection.

To validate simulation results, comparative plot as shown in Figure 16 is plotted. From contour plot of silencer at distance of 150 mm from L1, temperatures are obtained from experimental and simulation study for all

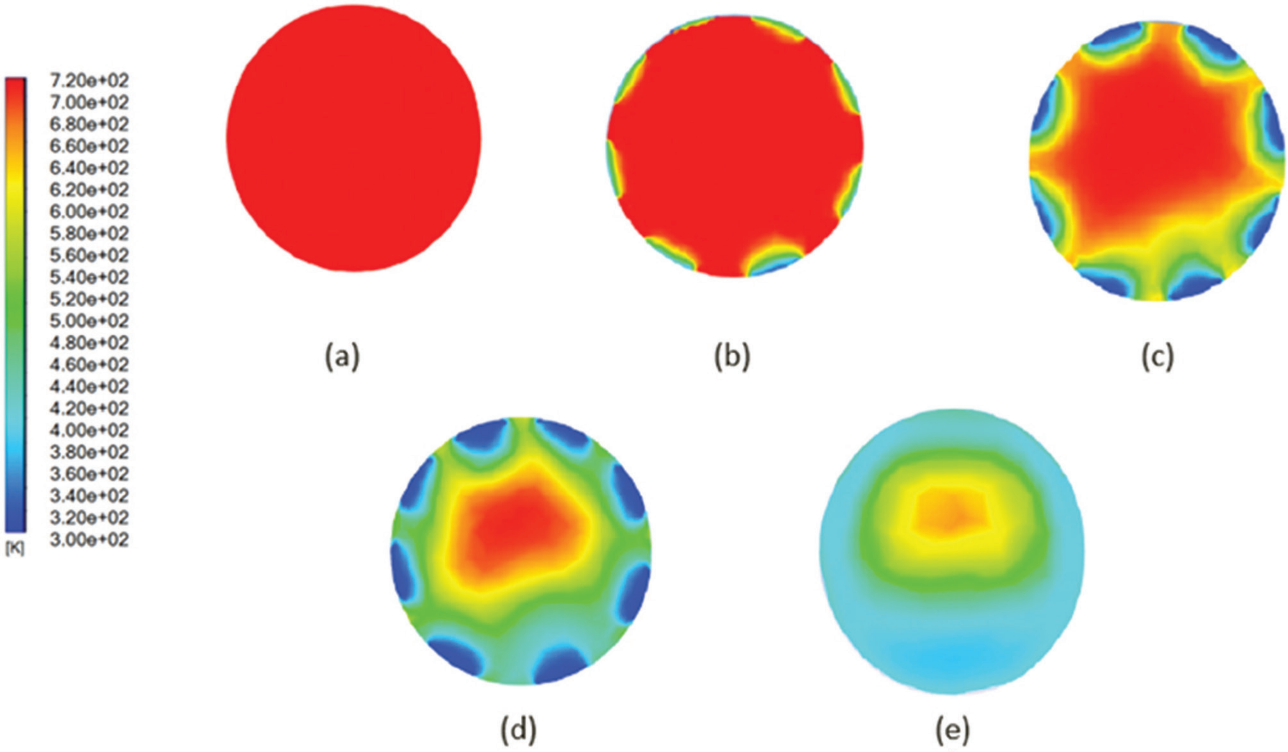

Figure 15. Temperature contours of silencer cross section for air injection at three planes.

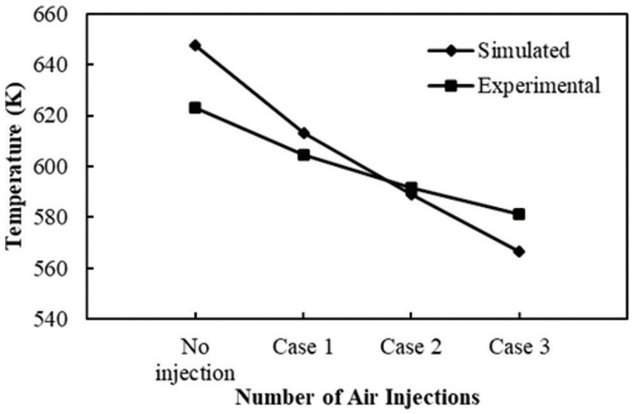

Figure 16. Comparison between simulation and experimental results.

the cases. Center point temperature reduces in simulation and experimental study with increase in planes of air injections. The temperatures obtained by simulation study are closed to experimentally obtain. The difference in temperatures between simulation and experimental results for no air injection is 24.44 K. The difference in temperatures between simulation and experimental results for case 1, i.e., one plane of air injection, is 8.87 K. The difference in temperatures between simulation and experimental results for two planes of air injections is 2.81 K. The difference in temperatures between simulation and experimental results for three planes of air injections is 7.68 K. The difference in simulation and experimental results in percentage is up to 4%. Due to mixing of the hot flue gases with injected air there are different temperature contours seen in contour plots.

CONCLUSION

The simulation and experimental study were carried out to study the effect of air injection on the temperature and noise level of engine silencer. As the number of radial air injection plane increases, the temperature of flue gases decreases due to availability of more air at high pressure. Also, as the air inlet pressure increases there is decrease in temperature of flue gasses with slight increase in pressure inside silencer. High pressure jets penetrate into high temperature flue gases helps to reduce overall flue gases temperatures. The experimental results show temperature drop of around 18 K in case of one injection location at 2 bar reservoir pressure compared to no air injection case. The experimental results show temperature reduction up to 41 K in case of three injection locations along the length at 2 bar reservoir pressure compared to no air injection case. OASPL is reduced by about 5.4 dB when air is injected at three locations with 2 bar reservoir pressure. It is observed from simulation study that compared to no air injection there is a slight increase in pressure inside silencer as the air is injected radially and the trend is similar. Radial air injection with higher pressure at multiple location is very effective for reducing temperature of exhaust gases and engine noise. But higher injection pressure may lead to rise in back pressure inside the engine. Therefore, there is a need to optimize the air injection pressure, number of injection ports, diameter of port and injection plane for improving the performance of silencer.

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