EXHAUST SILENCER USING WATER INJECTION

Brandan Cotton[1], Lewis Damin[2], Anthony Silvestri[3] and Carl Q. Howard[4]

The School of Mechanical Engineering,
The University of Adelaide, South Australia 5005, Australia
[3]Email: a1627334@student.adelaide.edu.au

Abstract

This paper describes results from the development of a water injection noise control system applied to an exhaust duct. A mist of water is introduced into an exhaust duct by injectors into the gas flow and is used to reduce the sound pressure level in the exhaust by several mechanisms, particularly through the absorption of energy required for the evaporation of the water vapour. This noise control method is investigated firstly with the aid of CFD software and then tested experimentally. The results from the CFD showed that there are significant reductions in temperature, pressure and hence energy of the flow. The experimental prototype injection system showed inconclusive results due to systematic error. The instrumentation noise floor in every test was approximately 100dB when the water injectors were activated. It is expected that the increase in the noise floor is created by the injected water causing vibrations in the pipe walls which is picked up by the microphone. It is proposed that a water injection based noise attenuation device could be effective with different implementation based on research theoretical results.

1. Introduction

Reciprocating internal combustion engines (ICE's) generate significant noise at the cylinder firing frequency and harmonics. Theoretical studies have shown that water injected into a gas stream attenuates sound due to three reasons, momentum changes due to stokes drag, heat transfer due to the temperature gradient of the hot exhaust gas relative to the cooler liquid and latent heat due to vaporization of the liquid into the gas phase [6]. This generates three characteristic attenuation frequency bands, two at high frequencies due to stokes drag and heat transfer and one at lower frequency due to vaporisation. Dependency of the frequencies on the properties of the liquid and in the case of the low frequency band, the liquid to gas mole fraction, enables potential flexibility in tailoring attenuation frequency bands to match that of exhaust systems and offers scope for active exhaust noise control. The frequency bands in which sound is attenuated is determined by: the Lewis number Le defined as Pr/Sc , the ratio of the Prandtl and Schmidt numbers, where $Sc = \mu\rho D$, the viscosity μ, density ρ and diameter D of droplets, η the latent heat, the ratio of the molar mass of the vapour and air the mass of the vapour [6]. Experimental verification of the low frequency affects was presented by Cole [1] and the technique has been used successfully in noise control in NASA space shuttle launches [4]. This paper aims to present a noise control mechanism that can be used to control the sound pressure level emitted by an ICE through application of this theory by injecting water into the exhaust flow.

2. Literature

Watters et. al. [9] presented a paper on acoustical behaviour on various engine test cell structures. Of note is the section that discusses jet engine noise attenuation by water injection. The noise attenuation across various octave frequency bands in relation to the flow rate of water injected is presented. It was shown that for all flow rates, higher frequencies were attenuated more than lower frequencies [9]. In addition, a range of water flow rates were tested ranging from 200 to 12500 gallons per minute. For lower flow rates, an attenuation of 2dB for lower frequencies and 10dB was found for higher frequencies. For higher flow rates, attenuation up to 10dB for lower frequencies and 30dB for higher frequencies was found [9].

Marble and Candel [6] gave a theoretical account of the sound attenuating effects that liquid droplets have when introduced into a gaseous exhaust system [6]. In this environment the liquid quantity is very small relative to the gas and the sound wavelengths in the exhaust are much greater than the inter-particle spacing. Under these conditions it is reasonable to assume that the liquid is continuously and evenly distributed about the gas and the liquid particles act as individual dipole sound sources that weakly perturb exhaust sound waves that can modelled as one dimensional plane waves. Consideration of the governing linearalised differential equations (DE) for thermodynamics and momentum then allowed Marble and Candel [6] to derive three equations that describe three different maximum frequencies f_1, f_2 and f_3 of attenuating sound generated by the liquid phase as:

$$f_1 = \frac{6\pi a\mu}{m} \tag{1}$$

$$f_2 = \frac{1}{\tau_T}\frac{C_p}{C_l}\left[1 + L_e X_v \beta \frac{\gamma}{\gamma - 1}\eta^2\right] \tag{2}$$

$$f_3 = \frac{X_p}{\tau_D}\left[\frac{1 - X_v + X_V\beta\frac{\gamma}{\gamma-1}\eta^2}{1 + L_e X_v \beta\frac{\gamma}{\gamma-1}\eta^2}\right] \tag{3}$$

where, a is the diameter of droplets assumed to be of spherical geometry, μ is the viscosity of liquid, m is the mass of the liquid drop, C_p and C_l are the heat capacities of ideal gases at constant pressure and liquid heat capacity respectively, X_p and X_v are the mole fractions of liquid and vapour particles in the gas respectively, β is the molecular weight ratio of vapour to air, γ is the ratio of heat capacities, η is a term representing the latent heat of the vapour, τ_D is the diffusion relaxation time, τ_T is the thermal relaxation time, L_e is the Lewis number which is the ratio of the Schmidt and Prandtl numbers.

The first frequency f_1 arises due to Stokes drag (momentum) factors of the liquid droplets in the gas, the second frequency f_2 arises due to thermal heat transfer between the liquid and gas and the third frequency f_3 arises due to vaporisation of the liquid into the gas. The second frequency f_2 varies from being about equal in value to f_1 to up to twice its frequency for larger values of the latent heat η due to equation (2) having a quadratic dependence on η. However the smallness of the mole fraction of vapour relative to the gas X_p means that the third frequency f_3, directly proportional to this quantity is usually much lower in frequency relative to the other two. In practice, due to the limitations of the theoretical considerations, including departure from linearalised DE behaviour, the actual frequencies appear as frequency bands distributed about these maximums. These circumstances and the large dependence of the frequencies on the various properties of the liquid droplets allows for broad band attenuation that has potential to be tailored to suit a variety applications. This is coupled with the fact that they found water droplets introduced near the walls of ducts appeared more effective that those further away suggesting another significant optimisation considered later in the project.

Kandula and Lonergan, [4] conducted another theoretical study into the noise reduction caused by introducing water jets into exhaust emissions with considerable force. This technique was used to attenuate excessive noise generated during gas expansion from the engine nozzles of NASA space shuttle launches. They found a key factor affecting the attenuation is the velocity of the input jet spray, highlighting a variable which could be optimised. However, somewhat interestingly, Kandula and Lonergan [4] emphasised that few studies had been carried out for water droplets and the work of researchers such as Marble and Candel considered in the previous paragraph were not applicable to jets. In hindsight this study was for high velocity rocket and jet expansion of gases making the environment significantly different from that of the exhaust. However, Marble and Candel, [6] applied their theory to the practical case of turbofan jet exhaust, more extreme conditions than would exist in a piston engine exhaust which is the focus of this project. As such it will be determined if water jet sprays varying the water jet velocity could be effective at attenuating sound in piston engine exhausts.

An experimental investigation by Krothapalli et al, [5] showed that the noise created by high speed jet flow was characteristic of the unsteady turbulent flow structure. The injection of water into high speed jet flow modified the turbulent pattern formed by the out coming gas flow resulting in 10% to 30% reductions in axial and normal velocity components [5]. This new flow regime resulted in sound reductions of 2 to 6 dB depending on the injection location and the mass flow rate of water injected. The concept of modifying the turbulent behaviour of the flow is further supported by Henderson [3].

Norwood and Chen, [7] presented a paper on using water injection as a method of reducing the bubble noise from submarine engine exhausts. Their setup consisted of measuring the sound from a submerged nozzle fed with regulated compressed air and water via a flow meter. Hydrophones were lined up vertically parallel to the flow and were used to measure the sound produced from the exhaust bubbles. The acoustic emission of the exhaust jet at airflow rates from $0.32l/s$ to $1.72l/s$ and water injection rates between 0 l/s to 0.08 l/s was investigated. It was found that noise reductions of approximately 10dB could be obtained by injecting approximately 10% water, by volume, uniformly into the discharging air [7]. They also found that sufficient mixing of the water and air in the exhaust was important to get the optimal noise reduction.

Research performed by Ragaller et. al. [8] describes the effects of injection medium density and injection frequency. This work is mainly concerned with supersonic jet noise and so discusses the implications of extra weight on the aircraft due to the injection medium. Ragaller concludes that water is an effective noise suppressant but has a density of 1000 kg/m^3 making it inefficient to carry large quantities [8]. Ragaller suggests that by varying the injection frequency, pressure and duty cycle results in changes to the noise level reductions [8]. Ragaller performed tests in a combustion blow-down facility fitted with twelve circular array microphones. Water was injected into the gas flow at various frequencies using modified Bosch fuel injectors at the nozzle exit. For a constant injection pressure at a set gas flow temperature it was concluded that the higher the duty cycle, the better the attenuation. As such, continuous injection provided the largest attenuation in noise. It must be noted that their research was performed in supersonic flow conditions rather than the subsonic flow conditions found in a ICE exhaust system. Ragaller also concluded that work performed by Krothapalli et al, [5] that describes that injected water modifies the turbulent structure of the flow, does in fact lead to reductions in noise.

Studies conducted by Henderson, [3] at the NASA Glenn Research Center summarises findings over the last 50 years in the area of water injection for noise reduction purposes. Both subsonic and supersonic flow cases are considered and the injection of water and air is presented. Henderson, [3] concludes that water injection into gaseous flow reduces noise produced by three dominant mechanisms. The injection of water into the flow causes reductions in flow velocity via momentum transfer, reductions in flow temperature via evaporation and modifies the turbulent mixing that occurs within the flow as it travels [3]. These conclusions are complimentary of those discussed by Marble and Candel, [6] which showed that water injection caused momentum changes due to stokes drag, heat transfer due to the temperature gradient of the hot exhaust gas relative to the cooler liquid and latent heat due to vaporization of the liquid into the gas phase, [6].

From the literature reviewed there is significant research done in the area of using water as a noise attenuation mechanism. There is significant understanding in the physics of how water attenuates noise, [6], and has been used in a practical settings such as space shuttle launches and jet noise reduction at both the subsonic and supersonic case [4]. However, little research has been performed to determine whether this mechanism is effective in an ICE exhaust. All previous research was focused on applications where there was a constant gas flow. For the work considered in this paper, noise attenuation from a pulsating gas flow is considered. Little research other than that outlined by Ragaller et. al. [8] for a supersonic flow case has been performed on the effects of injection pulsing frequency. As such, the effectiveness of water injection in an ICE exhaust will be discussed in this paper.

3. Computational Fluid Dynamics

A rudimentary Computational Fluid Dynamics (CFD) model was developed to qualitatively confirm literature findings and justify building an experimental prototype.

3.1. Model Overview

A simple steady state, multi phase model (using hot, turbulent air and water) was made in ANSYS Fluent Release 16.0 to check that the water injection would sufficiently absorb energy from the flow in the form of temperature and pressure reductions. It was expected that Fluent would not be able to successfully model all mechanisms that result in acoustic attenuation in the flow, and as such the model was kept simple and qualitative.

3.2. Geometry and Mesh

The exhaust was modelled based on geometry used in the experimental setup, albeit with four injection points instead of the three that was eventually used for experiments. The wall was designed based on 16 gauge steel pipe with convection effects included. The expansion chamber used in the geometry was present in the experimental setup and was included to represent a typical exhaust system resonator, adding more realistic turbulent effects to the gas flow. An exhaust outlet length of 2m was used to give the flow time to develop. Mesh was generated using the sweep method and inflation was used at the boundaries to adequately model velocity boundary layers. The geometry and mesh is shown in Figure 1.

3.3. Results

Figure 2 shows the mass fraction of water in the pipe. Successful injection of water can be seen at the injector locations. It can be seen that the water is highly subject to the effects of gravity and collects in the bottom of the pipe downstream of the injection points. Figure 3 shows the temperature profile in the pipe. It can be seen that there is a large reduction in temperature downstream of the injection points. A significant amount of heat transfer has occurred from the flow due to the large temperature gradient between the gas flow and the injected water. Of note is that the temperature drops below the boiling point of water (373K) indicating the possibility of condensation occurring. As such a water catchment tank was fitted to the test apparatus. The results also show a significant decrease by approximately a factor of 2 in dynamic pressure, as well as the velocity of the flow downstream of the injector locations. As the flow velocity has been reduced, a change in flow momentum has resulted. Together, these results indicate that the sound pressure level of the flow downstream of the injectors has reduced as there is evidence of all three primary mechanisms of sound attenuation by water injection.

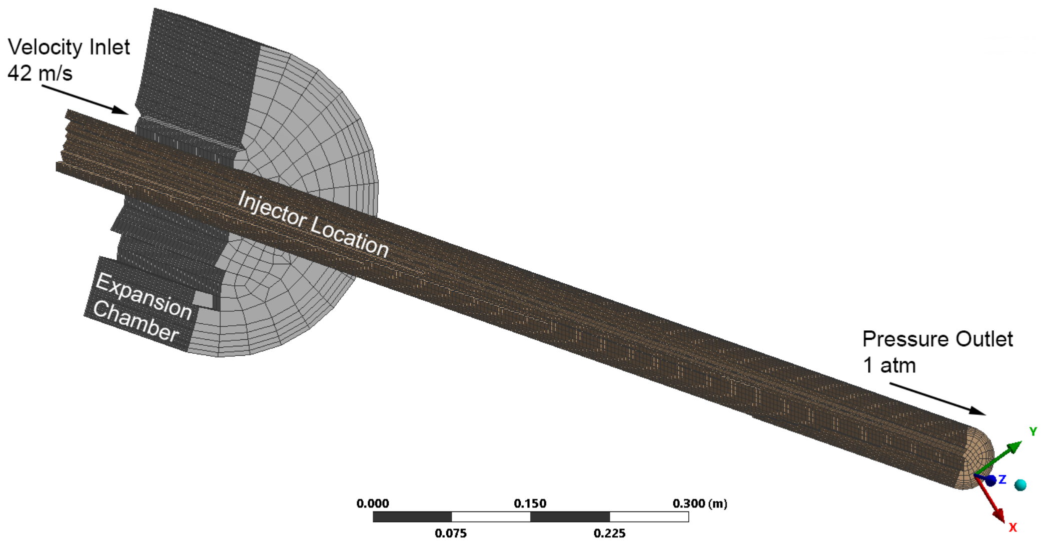

Figure 1: Section view of mesh used in CFD

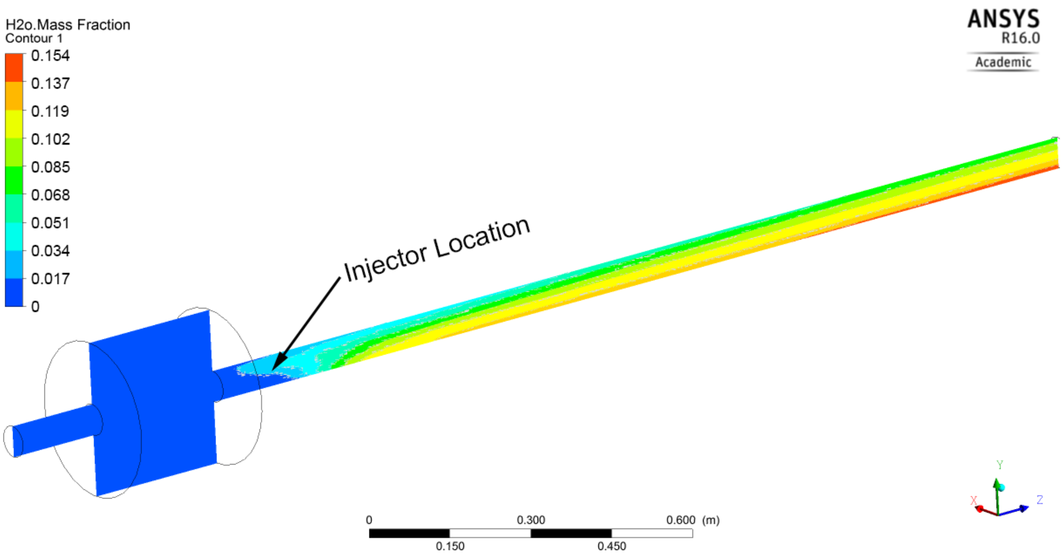

Figure 2: CFD results showing the water mass fraction profile in the exhaust duct.

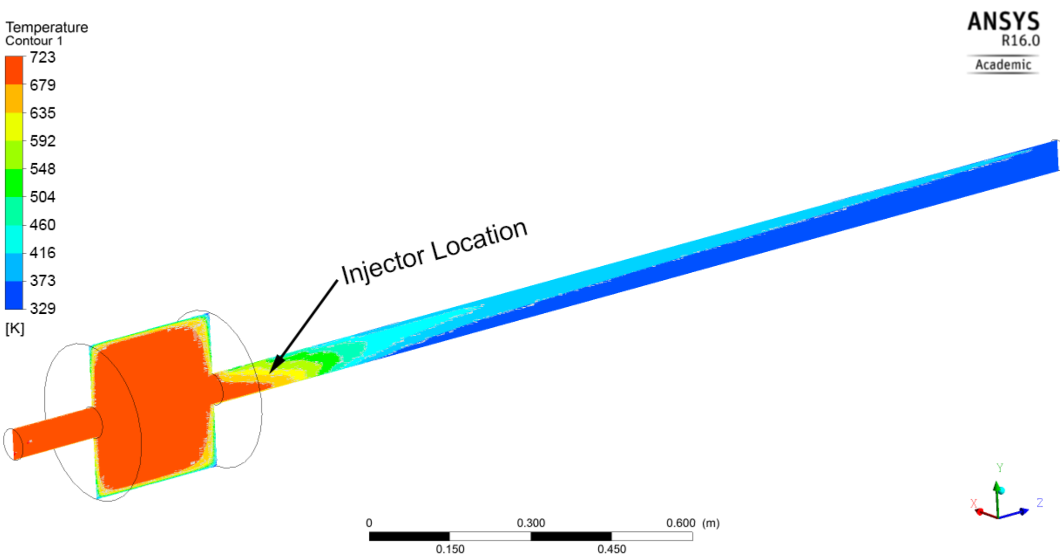

Figure 3: CFD results showing the temperature profile in the exhaust duct.

4. Sound Attenuation by Water Injection

As the results from the CFD model suggest that water injection leads to reductions of the temperature and dynamic pressure of the gas flow, it is likely to lead to reduction in noise. Hence, an experimental rig was built that injected water into the exhaust of an automotive engine. This method employs the use of fuel injectors from a gasoline direct injected engine, the fuel rail and a high pressure water pump. The injected water will affect the flow by absorbing energy present in the flow and change the acoustic response.

4.1. Water Injection Equipment

The temperature of the exhaust gases of the ICE that the system is designed for are approximately 450 degrees Celsius. Three General Motors SIDI direct injectors were used as they are well suited to work under high temperatures. The injectors are mounted to a fuel rail as it provides a means of water delivery and support for the injectors. Due to their small size the injectors are mounted to the exhaust using a liquid cooled solid machined housing which can be seen in Figure 4.

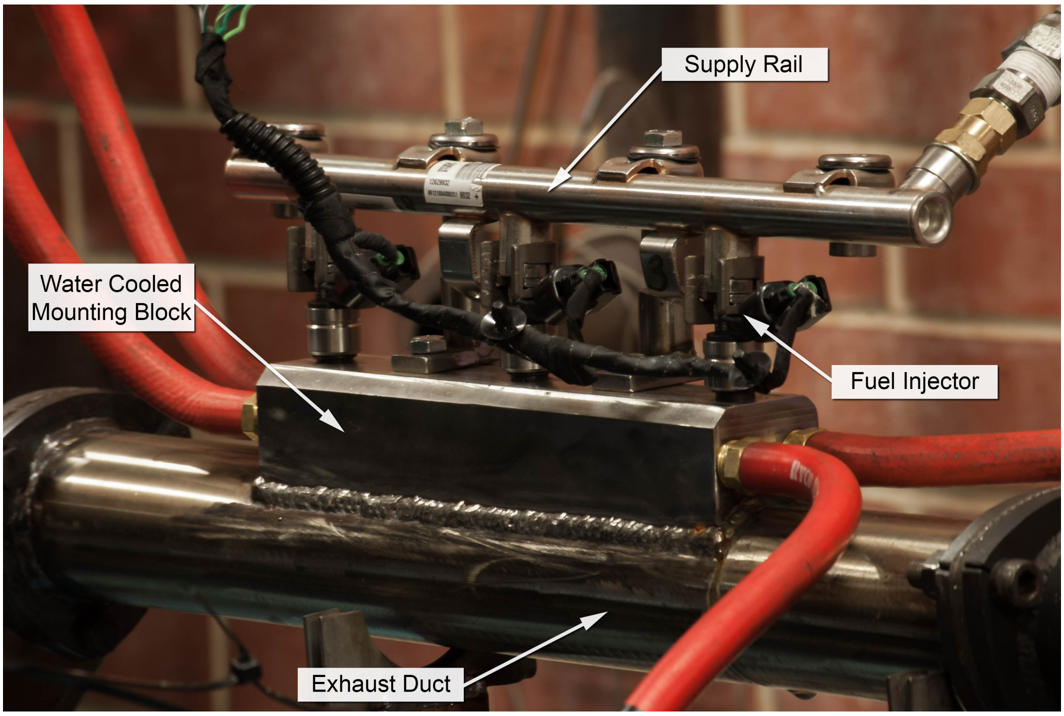

Figure 4: Photograph of the modified fuel injectors and water cooled mounting block

The water pumped through the injectors is required to be at a pressure of 2MPa to 15MPa [2]. To achieve these pressures, a Karcher K2.100 High Pressure Cleaner was attached to the fuel rail to provide the water pressure to supply the injectors.

The injectors are controlled by an electronic signal generator allowing individual control of pulse width and duty cycle. The signals are applied to MOSFET's allowing a 12V supply to open the injectors as required. The chosen injector timing opens each injector one at a time with approximately a 40% duty cycle giving a slight overlap to allow for the time taken for the nozzle to open. This ensures a continuous stream of atomised water. Further development of the injector driver system will allow a tachometer input to control injector timing, to coincide with the arrival of pressure pulsations.

This injection system was installed into a V6 petrol engine exhaust system. The engine was controlled by a dynamometer allowing accurate control of RPM and engine load. A microphone was installed approximately one metre downstream to measure noise reduction. Two K-type thermocouples were installed to measure upstream and downstream temperatures.

5. Experimental Results and Discussion

The water injection set up was tested at several engine operational conditions. The engine speed (RPM) and load applied (Nm) were varied to see how the effectiveness of the injection system changed.

The primary engine testing was conducted at 2000RPM (cylinder firing frequency of 100Hz) with a 90Nm Load applied to the engine by the dynamometer. Figure 5 shows how the sound pressure level (SPL) varied with and without water injection over the 12000Hz range. Figure 6 shows the SPL response of the engine at 3000RPM with a load of 50Nm. Similar behavior can be seen to that shown in Figure 5 at 2000RPM and 90Nm.

As it can be seen in both Figures 5 and 6, the measurement noise floor with the injectors operating is approximately 100dB. This is an unusual result and suggests some systematic error in the recording as it is substantially greater than the noise floor of the engine alone. To measure the source, the injectors were run while the engine was off and the SPL was measured. It was found that the noise floor of the injectors alone was also approximately 100dB as seen in Figure 7. To isolate the source of this noise, the injectors were run with no water passing through them. It can be seen in Figure 7 yet again that the noise floor is significantly lower than with the water on. This suggests that the noise is not due to electromagnetic interference as if it was the case, the noise floor issue would be present with no water. This in turn suggests that the injected water is the cause of the noise. To determine this, the injectors were run with water supplied and the microphone suspended in the exhaust outside of its housing, isolated from the pipe walls. It can be seen in Figure 7 that the noise floor measured in this scenario is approximately 70dB. These results suggest that there is some form of vibration in the pipe walls that is picked up by the microphone which would explain the unusual results obtained during testing.

Based on literature reviewed and computational models, the idea of an exhaust silencer for an ICE based on water injection is plausible, however the implementation described in this paper has some flaws. For a design in future, it is necessary to reduce the noise in the pipe walls from the injected water. Angling the injectors such that the water injected is not perpendicular to the exhaust flow may be one way of achieving this.

Another notable result is the temperature reductions achieved by water injection. At 2000 rpm under 90 Nm of load, the exhaust temperature was reduced to 110 C from 430 C. Exhaust gas temperatures were dependant on engine speed. Higher speeds resulted in higher temperatures (as much as 600 degrees Celsius at 4000RPM) and less cooling was achieved, likely due to the increase in flow rate and volume of exhaust gas giving less time for heat transfer to occur. These results help to validate the CFD analysis performed.

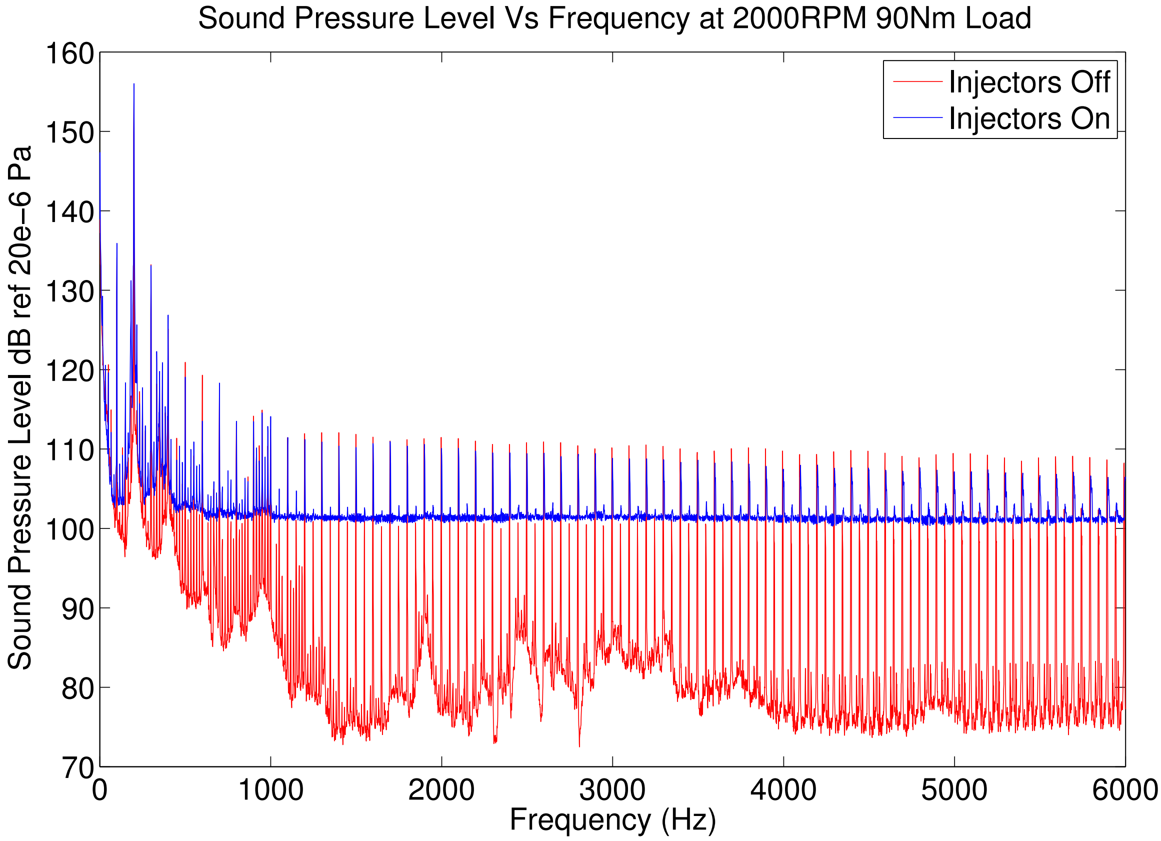

Figure 5: Sound Pressure Level Vs Frequency with and without water injection

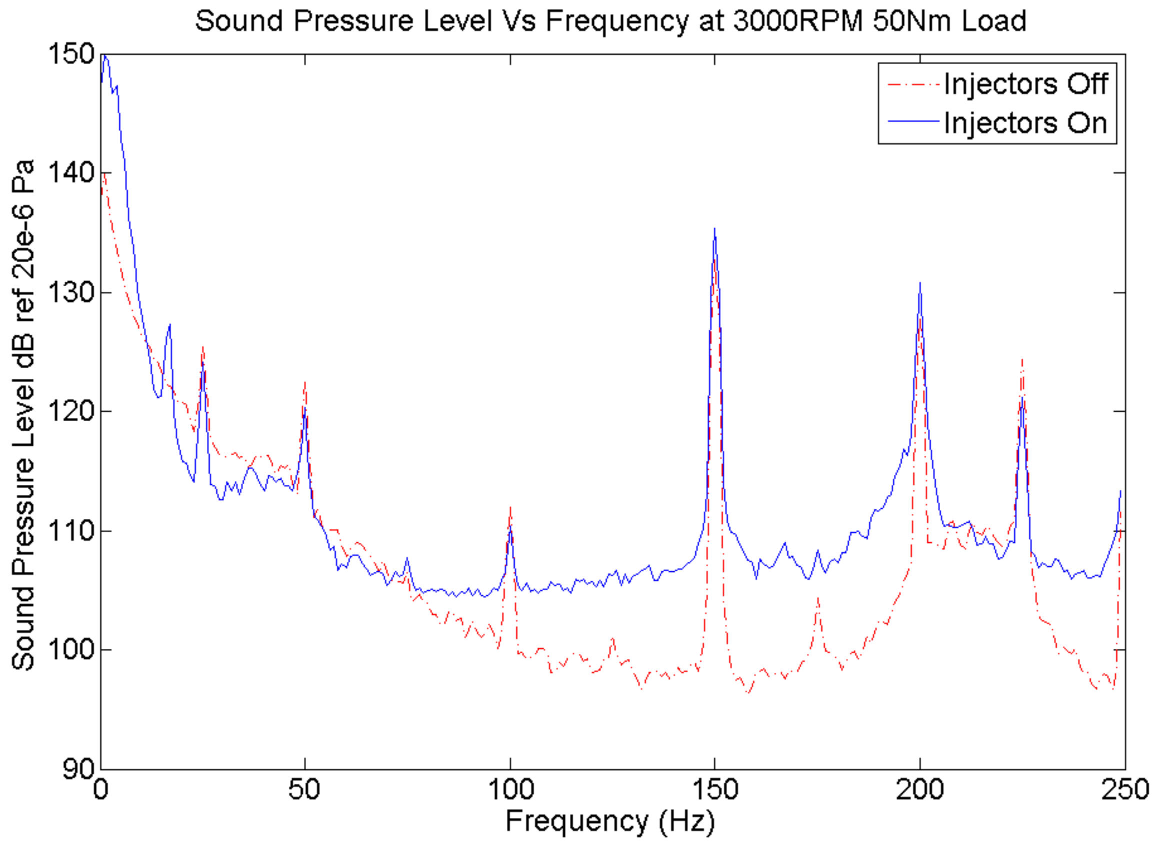

Figure 6: Sound Pressure Level Vs Frequency at 3000RPM and 50Nm Engine Load

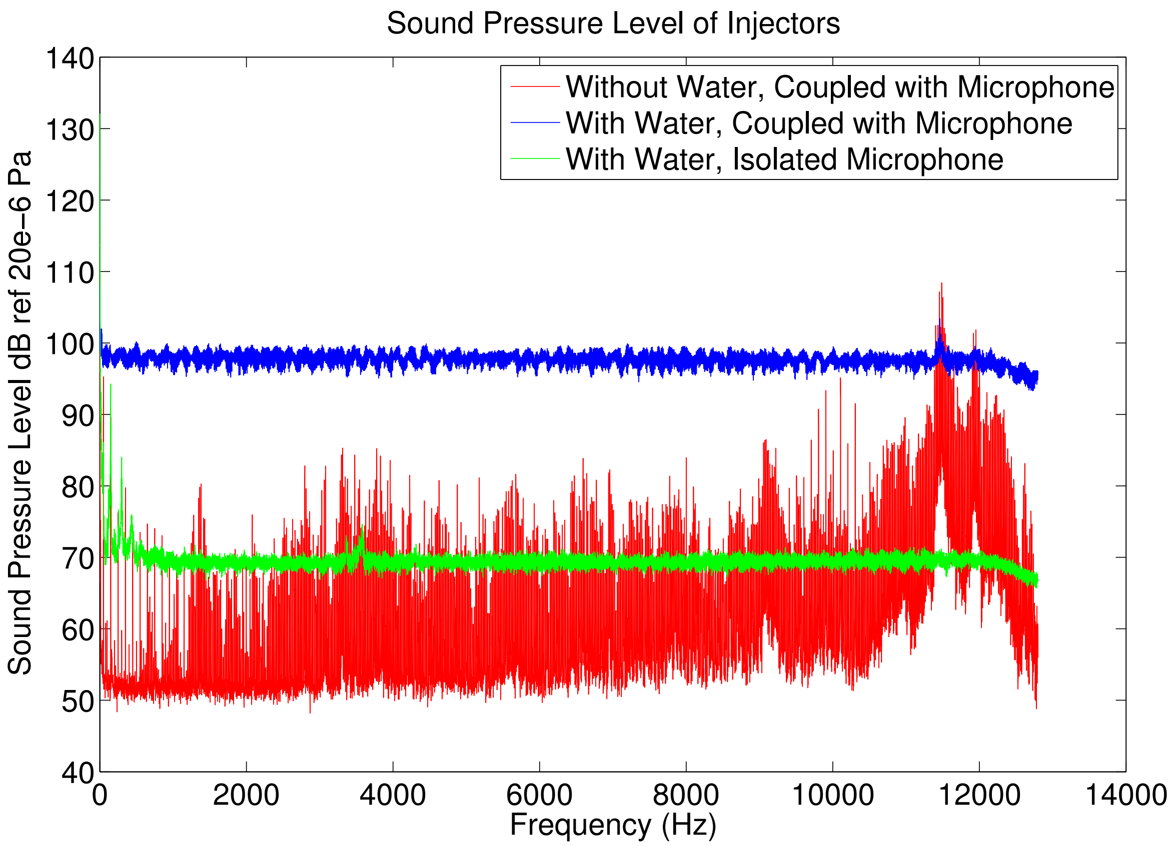

Figure 7: Sound Pressure Level Vs Frequency for varying injector and microphone states.

6. Conclusions

The experimental prototype injection system showed inconclusive results due to systematic error that took place. The noise floor in every test was approximately 100dB when the water injectors were activated. It is expected that the noise floor is created in the results by the injected water causing vibrations in the pipe walls which is picked up by the microphone causing unexpected behaviour in the results. It is proposed that a water injection based noise attenuation device could be effective with different implementation based on theoretical results. Temperature reductions of over 300 degrees Celsius were evident that validated the CFD model. Future work will require the microphone to be isolated from any exhaust duct vibration to ensure that there is no distortion in the results. Furthermore, an active control system could be developed for the injectors such that the water is injected at points that coincide with the fundamental engine firing frequency.

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