Are the dynamics of fluid injection a mechanism of improving the acoustic characteristics of performance exhaust mufflers?

Journal of Physics: Conference Series

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Abstract. Perforated tubes are used extensively in industry for various applications. Oil well completion and draining systems are examples of such applications. These applications involve the lateral injection of an incompressible fluid through the perforations. The injection of fluid alters the characteristics of the flow inside the tube. Hence, numerous investigations have been conducted in this field in order to gain insight on the dynamics of pressure drop when perforations and fluid injection are present. The trends seen from pressure drop fluctuations validated the acoustic damping effect of perforated tubes in the absence of injection. These results also encourage the use of perforated tubes in exhaust mufflers. In addition to the perforation effects, fluid injection has the potential to enhance the damping effect even further. Are the dynamics of fluid injection a mechanism of improving the acoustics characteristics of performance exhaust mufflers?

1. Introduction

Internal combustion (IC) engines are the most widely used energy sources employed in self propelled vehicles. The wide acceptance of these engines has resulted in the engines contributing significantly towards global warming [1]. Thus, improving the efficiency of the IC engine has become a priority for scientists and engineers.

The indicated power output of a typical or normally aspirated IC engine is proportional to the volumetric displacement of the engine [2]. The net power output and efficiency of the engine is depended on numerous variables. The exhaust system is an example of one of the variables, which affect the efficiency of an internal combustion engine [3].

A basic exhaust system performs multiple functions. However, this paper focuses on the functions of conveying exhaust gases from the combustion chamber to the environment and that of acoustic damping. Such an exhaust system can be modelled as a network of plain (smooth tubes) and perforated tubes [3]. The plain tubes are employed for the function of conveying exhaust gases and perforated tubes for acoustic damping. Perforated tubes are housed inside mufflers, which are mounted at strategic points along the length of the exhaust system. Ordinary, exhaust mufflers provide damping by restricting the flow of exhaust gases. This process increases the pumping working done by the engine and reduces the efficiency of the engine in the process [3].

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In high performance applications, performance exhaust mufflers are employed to reduce the losses associated with ordinary mufflers [3]. These mufflers are usually constructed as straight and single pass perforated tubes. This configuration results in a reduction of pumping work and come with the penalty of increased noise. Thus, performance mufflers are reserved for exotic or recreational vehicles.

There are other applications, which employ perforated tubes in a similar configuration to the one used in performance exhaust mufflers. Oil well completion [4][5][6] and draining systems [7][8] are examples of such applications. Research conducted in these fields confirm that fluid flow through perforated tubes have different characteristics when compared to the flow in smooth tubes [8]. These studies also include the injection of fluid through the perforations since it is critical in draining applications. The injection of fluid causes fluid acceleration inside the perforated tube. The process alters the characteristics of flow inside perforated tubes even further [9].

There have been few attempts in literature, which investigate the propagation of pressure fluctuations and, possibly acoustic characteristics of perforated tubes when fluid injection is present. Hence, the purpose of this paper is to discuss the fluctuation of pressure drop measurements when fluid injection is present for perforated tubes with an ideal perforation pattern.

2. Literature review

In this section, the literature, which is aligned with the tested experimental set-up is discussed first and then, the primary sources of pressure and/or pressure drop fluctuations are mentioned briefly. The latter subsection is concluded by comparing the pressured drop fluctuations generated by the experimental set-up to the noise generated by an engine.

2.1. Perforated tubes with fluid injection

Experimental studies are conducted for perforated tubes with fluid injection since the behaviour of flow under these conditions is fundamentally different to the conditions observed in smooth tubes without any perforations [8][9]. Most of the experiments were conducted under turbulent conditions. The research was utilised to gain insight on the behaviour of the lateral inflow of oil and water during oil well completion [4][5][6] and draining operations [7][8] respectively. This literature focuses on the injection of an incompressible fluid into a perforated tube under turbulent flow conditions.

The results obtained in literature indicate that perforation roughness and fluid acceleration effects are the major variables influencing the losses experienced in perforated tubes [9]. The influence of perforation roughness is more pronounced in the absence of fluid injection [6]. Perforation roughness is directly proportional to the porosity of the perforated tube provided the perforation pattern is preserved [8]. Fluid injection does not reduce perforation roughness or losses unless the effects of fluid acceleration are reversed [6]. A diffuser is a practical manner in, which the fluid can be decelerated before being discharged into the environment [10].

2.2. Sources of pressure or pressure drop fluctuations

Turbulence in a homogeneous incompressible fluid under adiabatic conditions is characterised by the fluctuation in volume flow rate and pressure drop [10]. Thus, turbulence is the first obvious source of pressure fluctuations. Researchers suppress turbulent fluctuation by obtaining multiple measurements, which are averaged to describe the state of the flow under steady conditions [11]. This implies that turbulent fluctuations act as disturbances or measurement noise during testing.

Most experimental facilities [9][11] use a motor with speed drive to regulate the flow rate through the experimental setup. This arrangement, especially when a centrifugal pump is used, generates flow and pressure pulses throughout the entire experimental setup. Accumulators are often installed to dampen pressure and flow pulses in order to reduce the deviation of flow measurements.

It can be observed that a centrifugal pump in an experimental setup (figure 1), is analogous to an IC engine. Both act as pumps and generate pressure pulses while they are operational. In a lab environment, the pump draws water from a vented reservoir, which is at atmospheric pressure and then pumps the fluid through the test section until it return to the reservoir. An internal combustion causes a similar process for the air that flows through the engine. However, there are differences between the two since air is compressible [10].

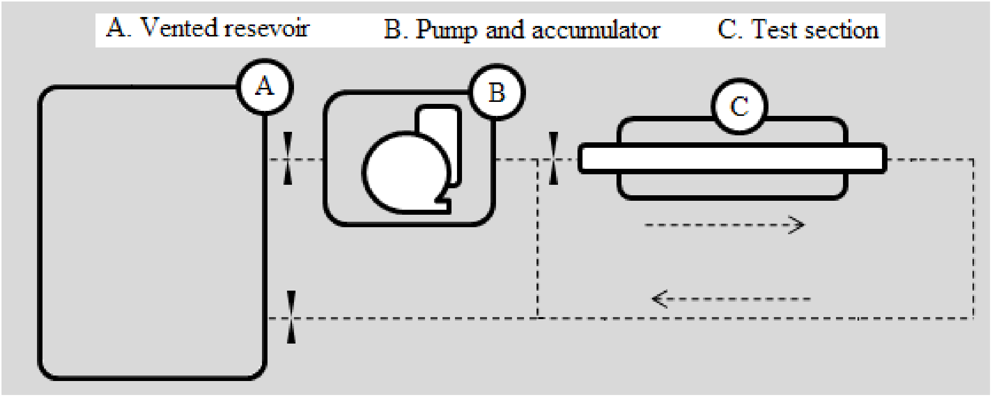

Figure 1. Typical single phase experimental set-up

3. Experimental setup

In this section, the experimental set-up and test sections are described. The subsection is followed by the scope of experiments and the data reduction method. The section is then concluded by a case study, which indirectly validates the data reduction method.

3.1. Experimental set-up and test sections

The experimental set-up used for the study is similar to the one depicted in figure 1. An additional line with an independent pump and accumulator was installed to regulate the injection flow rate, which was introduced into the test section through the annulus of the test tube. Coriolis flow meters and filters were connected in series and downstream of the pump subsystem to measure flow rate and filter debris.

The test sections were manufactured from copper fittings and were joined together using the lead-tin soldering technique. The perforated tubes had an inner and outer diameter of 20.8 mm and 22 mm respectively. The total length of tube was 1.7 m. This length was divided into three segments for establishing entrance and exit conditions before and after the central segment, which contained perforations. Table 1 summarises the lengths of the segments.

Table 1. Length of test section segments

Segment	**Length**
Entrance	450 mm
Perforated	800 mm
Exit	450 mm

Three test sections with different perforation patterns were tested. The reference or base pattern was derived from literature [8]. The perforation pattern had a row of seven 1.5 mm diameter perforations, which were equi-spaced around the circumference of the tube. The second row and subsequent even numbered rows were staggered to the odd numbered rows. This pattern formed equilateral triangles with a pitch of 7.8 mm. The remaining patterns were derived by stretching the base pattern in the direction of the flow. Thus, the equilateral triangle perforation pattern collapsed into isosceles triangles with perforation pitches of 15.6 mm (medium tube) and 31.2 mm (coarse tub)[9].

3.2. Scope of experiments and data reduction method

Water was used a test medium and the Reynolds numbers for the experiments ranged from 19 000 to 60 000. The injection flow ratio was varied between 0% and 5% of the exit flow rates. Sixty (60) measurements were logged at a frequency of 2 Hz for each of the 135 different data points.

The flow rates or Reynolds numbers were obtained by averaging all the flow rate measurements for a given data point. Sound propagation or pressure fluctuations were approximated from individual pressure drop measurements. Therefore, the fluctuations for this study are referred to as pressure drop fluctuations to consider the influence of the turbulence noise measured at both the inlet and outlet pressure taps. The pressure drop fluctuation or percentage fluctuation, *pf*, from the mean pressure drop is defined by equation (1).

$$pf_i = \left|\frac{\Delta P_i - \Delta\bar{P}}{\Delta\bar{P}}\right| \times 100\% \qquad (1)$$

3.3. Validation case study

The experimental set-up was not intended to measure pressure drop fluctuations. Hence, a validation case study is presented to create a frame of reference from, which subsequent pressure drop fluctuations results are compared.

An ordinary smooth tube without any perforations was used as such a reference. The average pressure drop or friction factor error for the smooth tube was 2.4% when the averages of the measurements are compared to literature [10]. It was then concluded that the experimental set-up yields results, which are within the limits of uncertainty of the experimental set-up and are comparable to common practice.

The smooth tube measurements, which were recorded at Reynolds number of 40 000 were reduced futher using equation (1) to obtain the percentage fluctuation of each measurement. The process was repeated with perforated tubes in the absence of fluid injection. The percentage fluctuation of a smooth tube (clear circles) and medium tube (solid triangles) are plotted in the appended figure (figure 3). Peak percentage fluctuation for the former is 54.1% and has an average fluctuation of 17.0%. The peak and average percentage fluctuation for a medium tube with perforations is 32.2% and 9.9% respectively. The moving average trend-lines indirectly validate that perforations (solid line) have the ability to dampen pressure drop fluctuations observed in smooth tubes (dashed line). Similar results are observed in performance exhaust mufflers fitted with perforated pipes [3].

4. Experimental Results

This section reports the influence of perforation pitch-diameter ratio and the effects of fluid injection on pressure drop fluctuation.

4.1. Perforation pitch-diameter ratio

The effects of perforation pitch-diameter for the tested perforations pattern are reported. Table 2 summarises the peak and average percentage fluctuation values at a Reynolds number of 40 000.

Table 2. Peak and average percentage fluctuation values as a function of pitch-diameter ratio at a Reynolds number of 40 000 with no injection

Pitch-diameter ratio	Pattern	pf_{peak}	$pf_{average}$
0.375	Base tube	41.4	14.8
0.75	Medium tube	32.2	9.9
1.5	Coarse tube	41.0	13.3

The percentage fluctuation values of all the perforated tubes are lower than those of the smooth tube under similar flow conditions. A pitch-diameter ratio of 0.75 provides the best damping for the pressure drop fluctuations generated within the experimental set-up. Unfortunately, the mechanism, which drives the damping, is not thoroughly understood and requires further investigation.

4.2. Fluid injection

The effects of fluid injection on the medium tube are shown in figure 2. The figure depicts the peak and average pressure drop fluctuation as a function of fluid injection. Average percentage fluctuation remained fairly constant with an increase in fluid injection. Significant drops in fluctuations were observed for injection rates between 2 and 3% injection. This effect is more pronounced when analysing peak percentage fluctuation values. Injection caused a sharp decrease in fluctuation levels for these injection rates. The results encourage the use of injection for adaptive damping applications.

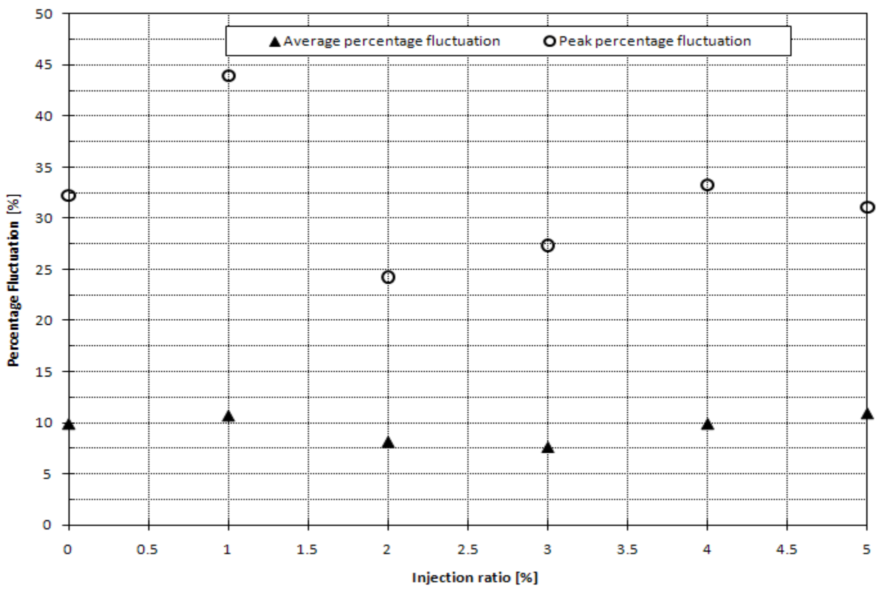

Figure 2. Percentage fluctuation as a function of injection for the medium tube

5. Conclusion

The wide acceptance of IC engines makes these engines extremely valuable in the day to day lives of many individuals and communities. The efficiency of these engines can be increased by reducing the pumping losses experienced in the exhaust system. Performance exhaust mufflers reduce pumping losses but they are usually louder than ordinary mufflers.

This paper drew an analogy between the behaviour of flow inside an exhaust system to that of an experimental set-up used for perforated tube measurements. The trend of the validation results were aligned with the expected results. The experiments identified an ideal pitch-diameter ratio for such a configuration. The peak percentage pressure drop fluctuations for this configuration is extremely sensitive to changes in injection ratio and opens the door for adaptive damping. Are the dynamics of fluid injection a mechanism of improving the characteristics of performance exhaust mufflers?

6. References

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Appendix A. Validation case study

Percentage fluctuation as a function of time for the smooth and medium tubes

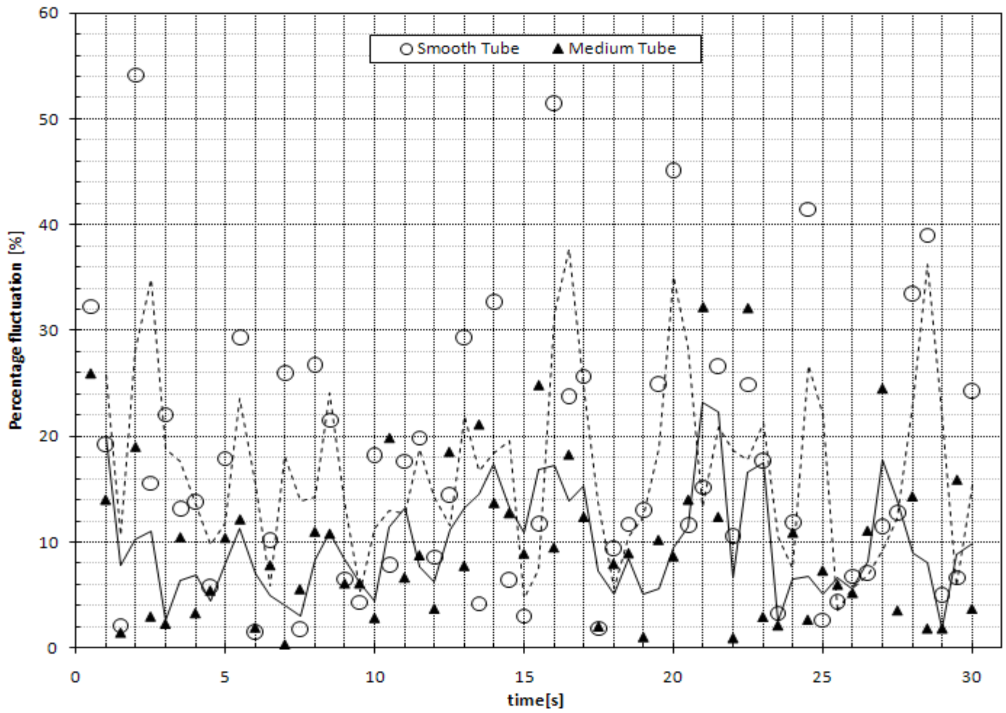

Figure 3. Percentage fluctuation as a function of time for smooth and medium tubes